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TECHNICAL REPORT K-83-4

CASE STUDY OF SIX MAJOR GENERAL-PURPOSE FINITE ELEMENT PROGRAMS

by

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US ARMY ENGINEER WATERWAYS EXPERIMENT STATION

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Computer program ANSYS	Finite element analysis
Computer program SAP	General-purpose finite element programs
Computer program STRUDL	Pre-processors
Computer program SUPERB	Post-processors
Computer-Aided Structural Engineering Project	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents a comparison of six general-purpose finite element programs (GPP's) and a brief examination of pre- and post-processors. The report was prepared to provide sufficient information to engineers within the Corps to enable them to make an intelligent selection of a GPP. The GPP's studied were SAP, E^3SAP, GTSTRUDL, MCAUTO STRUDL, ANSYS, and SUPERB.

The study involved a number of static, linear elastic analyses. The efficiency of the six GPP's typically used in the Corps was evaluated (Continued)

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20. ABSTRACT (Continued).

using a cantilever beam. Costs were computed for problems having the same bandwidth (BW) but varying degrees of freedom (DoF's) as well as for problems having the same DoF's but different BW's.

Two other problems representing typical Corps structures were also run using the same six GPP's. The first of these problems involved a concrete lock monolith on an elastic foundation. The second, a bulkhead, required an analysis of plate stretching and bending finite elements combined with the action of framing members.

The study also involved a comparison of some general-purpose pre- and post-processors that can be used in conjunction with the GPP's.

The report is meant only to provide data on some GPP's used in the Corps. Due to the rapid change in technology, constant improvements are made to the code. This coupled with the changes in computer cost algorithms makes it imperative for the user to verify and update the data in this report periodically. Also, since Corps' new computer contract has been awarded to CYBERNET, these studies need to be run in their system to be of maximum benefit. This will be done in a subsequent report.

PREFACE

This report provides a comparison of six general-purpose finite element programs and a brief examination of pre- and post-processors. The work was sponsored through funds provided to the U. S. Army Engineer Waterways Experiment Station (WES) by the Civil Works Directorate, Office, Chief of Engineers (OCE), under the Computer-Aided Structural Engineering (CASE) Project.

Definitions of the problems to be tested and the computer runs of the six general-purpose finite element programs were completed by the members of the CASE Task Group on Finite Element Analysis. Members of the group for this study were:

Mr. P. Thomas McGee, Nashville District, Chairman (left in Feb 83)
Mr. Richard Flauaus, St. Louis District
Mr. Richard Huff, Kansas City District
Mr. David Raisanen, North Pacific Division (current chairman)
Mr. Paul LaHoud, Huntsville Division
Mr. Jerry Foster, Federal Energy Regulatory Commission
Mr. Paul Noyes, Seattle District (joined in May 83)
Mr. Robert Hall, WES, Project Leader
Dr. N. Radhakrishnan, WES, CASE Project Manager

This report was initially compiled by Mr. H. Wayne Jones, Computer-Aided Design Group (CADG), Automatic Data Processing (ADP) Center, WES. The major portion of the comparison of the finite element runs and the pre- and post-processor work were completed by Mr. Robert L. Hall, CADG, and Dr. N. Radhakrishnan, Special Technical Assistant, ADP Center. The CASE Task Group worked in two groups to produce Appendices A and B and to edit the report. Dr. Kenneth (Mac) Wills, Georgia Institute of Technology, provided valuable input to this report.

An initial version of Appendix A: Comparison of Features of General-Purpose Programs was prepared by Mr. William Boyt, Structures Laboratory, WES.

The work was managed and coordinated by Dr. Radhakrishnan as CASE Project Manager. OCE point of contact for the work was Mr. Lucian Guthrie, Structures Branch, Civil Works Directorate. Mr. Guthrie also extensively reviewed this report.

Commanders and Directors of WES during the preparation and publication of this report were COL Nelson P. Conover, CE, and COL Tilford C. Creel, CE. Technical Director was Mr. Frederick R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY (NON-SI) TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary (NON-SI) units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
cubic inches	16.387064	cubic centimeters
feet	0.3048	meters
inches	2.54	centimeters
kip (force)-inches	112.9848	newton-meters
kips (1000-lb force)	4.448222	kilonewtons
kips (force) per square foot	47.88026	kilopascals
kips (force) per square inch	6894.757	kilopascals
pounds (force) per square foot	47.88026	pascals
pounds (force) per square inch	6.894757	kilopascals
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
square inches	6.4516	square centimeters

CASE STUDY OF SIX MAJOR GENERAL-PURPOSE FINITE ELEMENT PROGRAMS

PART I: INTRODUCTION

Background

1. As the power and flexibility of the finite element (FE) method have become apparent, engineers have become more and more interested in the use of general-purpose programs (GPP's) for employing this tool. Early FE method developments and uses were in the field of linear static analysis. Later strides came in dynamic, nonlinear, plastic, and soil-structure interaction analyses. Numerous reports, books, and articles are available that describe the theoretical aspects of these analyses; therefore, this report will not address these aspects.

2. A recent survey within the Corps of Engineers on FE method use (Radhakrishnan 1979) yielded some rather interesting results. Nineteen Corps offices reported that they had used FE analysis in the past 3 to 5 years. A total of 125 major projects were involved. As a result of this study, it was determined that a set of guidelines on how to present FE results to a reviewer was needed. These guidelines were published as an Engineer Technical Letter (ETL) 1110-2-254 (Headquarters, Department of the Army, Office of the Chief of Engineers 1980). It was also determined from the survey that most analyses were performed using GPP's. This report will address some of the most widely used GPP's in the Corps in the field of structural engineering and the pre- and post-processing capabilities which are available.

3. This report is meant only to provide data on some GPP's used in the Corps. Due to the rapid change in technology, constant improvements are made to the codes. This, coupled with the changes made in computer cost algorithms, makes it imperative for the user to verify and update the data in this report periodically.

Special-Purpose and General-Purpose Programs

4. Special-purpose programs (SPP's), as the name implies, are designed to solve a specific type of problem and are thus limited in their application.

GPP's, on the other hand, are designed to solve a broad class of problems (Radhakrishnan, Kirkland, and Cheek 1974). GPP's are also generally designed to handle one-, two-, and three-dimensional problems using finite elements of widely different behavior.

5. Generally, if an SPP is available that is pertinent to an analysis, it will be easier to use than a GPP. GPP's are more cumbersome to use and need more time and energy in both the preparation of input and the reduction of output data. GPP's also generally cost more to use than SPP's and need more resources to maintain and support. However, once use of a GPP is mastered for one problem, subsequent application to other types of problems becomes less difficult. Also, use of a standard GPP aids in transferring technology by providing the user the lastest analysis and/or design tools.

Requirements for a GPP

6. As minimum requirements, a GPP should:

a. Implement FE theory.

b. Have an adequate library of elements to allow proper modeling of a structure.

c. Have a bandwidth (BW) minimizer.

d. Check for numerical instability of the global stiffness matrix.

e. Have graphical pre- and post-processing capabilities.

f. Be maintained by a specialized staff available for consultation.

7. Also, a GPP should be selected with care. Codes should be avoided that:

a. Do not give correct results (perform verification studies).

b. Use outdated elements.

c. Do not completely solve the problem; e.g., do not compute reactions.

d. Do not use state-of-the-art solution, storage, and assembly techniques.

e. Do not allow for error checking of data.

f. Sacrifice usability for solution speed.

g. Provide no pre- or post-processing capabilities.

Purpose and Scope of Study

8. The purpose of this study is to provide sufficient information to

engineers within the Corps to enable them to make an intelligent selection of a GPP for their use. Since the selection of a GPP is dependent on the problem to be analyzed, a definite statement as to which is the best GPP for a particular problem will not be made. However, by benchmarking several GPP's which have been used within the Corps, the reader will have sufficient information to select a GPP for a given problem.

9. This study involved a number of static, linearly elastic analyses. The efficiency of six GPP's typically used in the Corps was studied using a cantilever beam (Part II). The costs were computed for problems having the same BW but varying degrees of freedom (DoF's) as well as for problems having the same DoF's but different BW's.

10. Two other problems that represent typical Corps structures were also analyzed using the same typical GPP's (Part II). The first of these problems involved a concrete lock monolith on an elastic foundation. The second problem, a bulkhead, required an analysis of plate stretching and bending finite elements combined with the action of framing members for which a GPP is very useful.

11. Part III compares some general-purpose pre- and post-processors that can be used in conjunction with the GPP's.

Future Work

12. Since the Corps' new teleprocessing contract has been awarded recently (June 83) to CYBERNET, the studies reported here need to be run in their system to be of maximum benefit. The results of the run will be presented as an update to this report during the next year.

PART II: COMPARISON OF SIX GENERAL-PURPOSE PROGRAMS

Introduction

13. Six GPP's being used in Corps FE method analyses were selected for this study. These include different versions of the same GPP, such as STRUDL, that are basically equivalent but run on different computers. This factor permitted cost comparisons at different computer sites. The GPP's studied were:

Program	Where Run
SAP	U. S. Army Engineer Waterways Experiment Station (WES)
E^3SAP	Boeing Computer Services
GTSTRUDL	Boeing Computer Services
MCAUTO STRUDL	McDonnell Douglas
ANSYS	Boeing Computer Services
SUPERB	Boeing Computer Services and INFONET

Features Comparison

14. Appendix A is a capability chart for comparing the above GPP's. This chart was compiled using available documentation on each program. It would be helpful to the user looking for a GPP with a specific feature or to someone beginning to use a GPP. The chart shows that most of the features in the programs are the same; however, methods of implementation may vary widely. The greatest difference in the programs is in their element libraries.

Element Libraries

15. Each GPP has an element library. The elements govern the usefulness of the GPP. For example, if a GPP does not have a plate bending element, it cannot solve plate bending problems. The elements also control such features as nonlinear material properties, body sources, surface loads, load types, and temperature effects. The more extensive the element library, the wider the variety of problems that can be solved by that GPP. Therefore, the element library is one of the most important features to be examined before using a GPP.

Efficiency Comparisons

16. It is difficult, if not impossible, to generalize on the efficiency of a GPP based on only one or two problems. One GPP may solve a given problem faster than another, but the reverse may be true for the next problem. Thus, to compare efficiencies, other fundamental characteristics of the GPP must be compared. One such characteristic is execution time, which is largely the time the GPP takes to solve a set of simultaneous equations. This time in turn is mainly dependent on the number of equations being solved and the BW. (This is not a valid statement, however, for GPP's that use a wave front technique for solution of equations.) The number of equations is proportional to the number of DoF's in the problem. Thus, in the first problem, a simple cantilever beam was modeled and analyzed using varying grids, with the total number of nodes changing but the BW remaining constant. In the second problem, the same beam was modeled and analyzed using a single grid numbered in such a way that it provided varying BW's. Both problems were solved using each of the six GPP's.

Problem definition

17. The 20-ft* cantilever beam shown in Figure 1 was analyzed using nine different grids. Grids Ia-Ie shown in Figures 2-6 have a constant BW of 46 with DoF's varying from 84 to 1008. Grids IIa-IIe shown in Figures 7-11 have 1000 DoF's but BW's varying from 14 to 504. It should be noted that some of these grids have elements with large aspect ratios (ratio of length to width of element) that could produce questionable results. While for this comparison study these grids with large aspect ratios are acceptable, they are not recommended for actual solutions of problems. In general, aspect ratios greater than four should be used with caution.

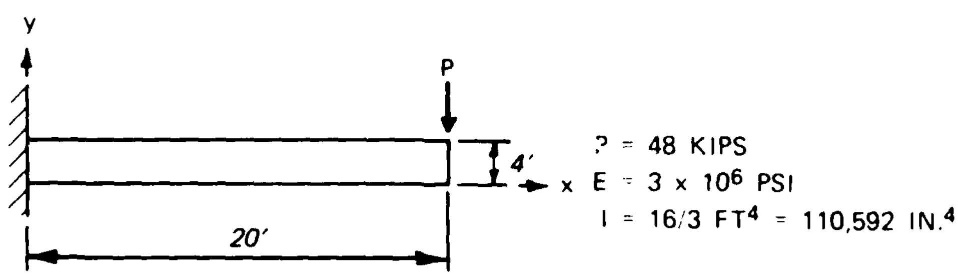

Figure 1. Cantilever Beam

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* A table of factors for converting U. S. customary (NON-SI) units of measurement to metric (SI) units is presented on page 3.

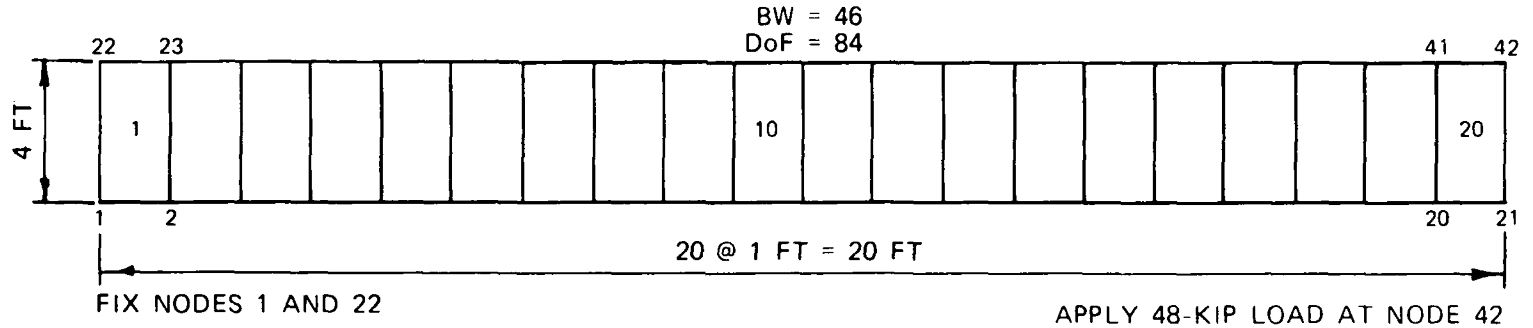

Figure 2. Grid Ia

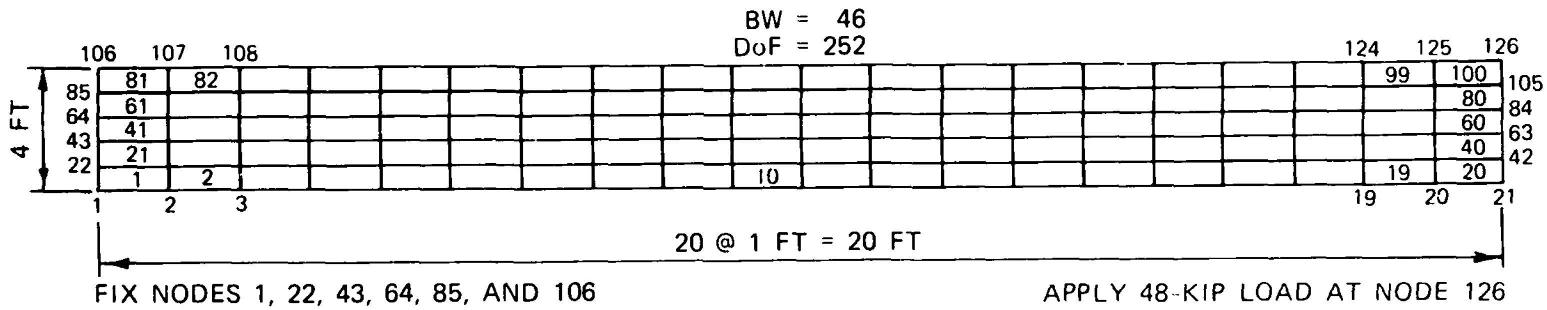

Figure 3. Grid Ib

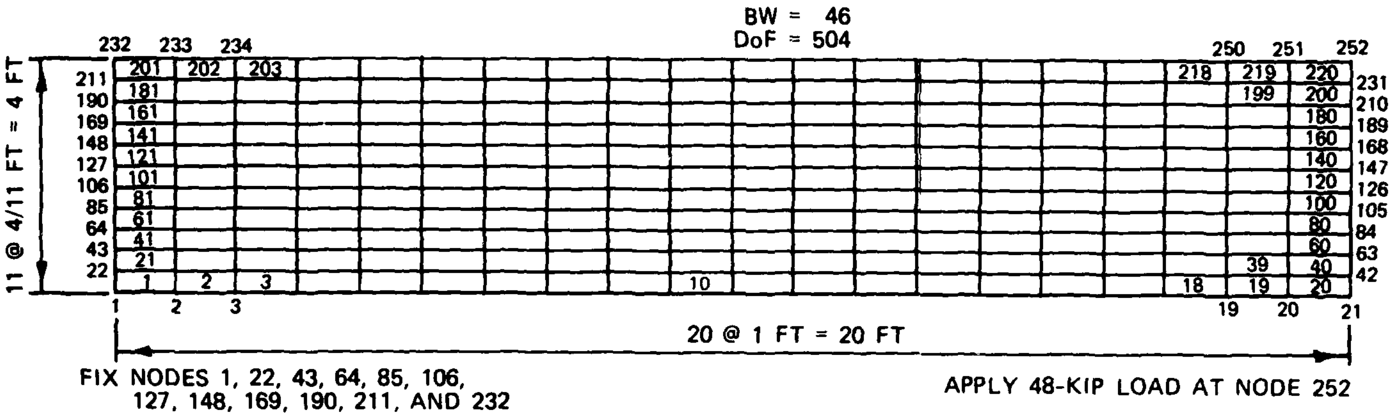

Figure 4. Grid Ic

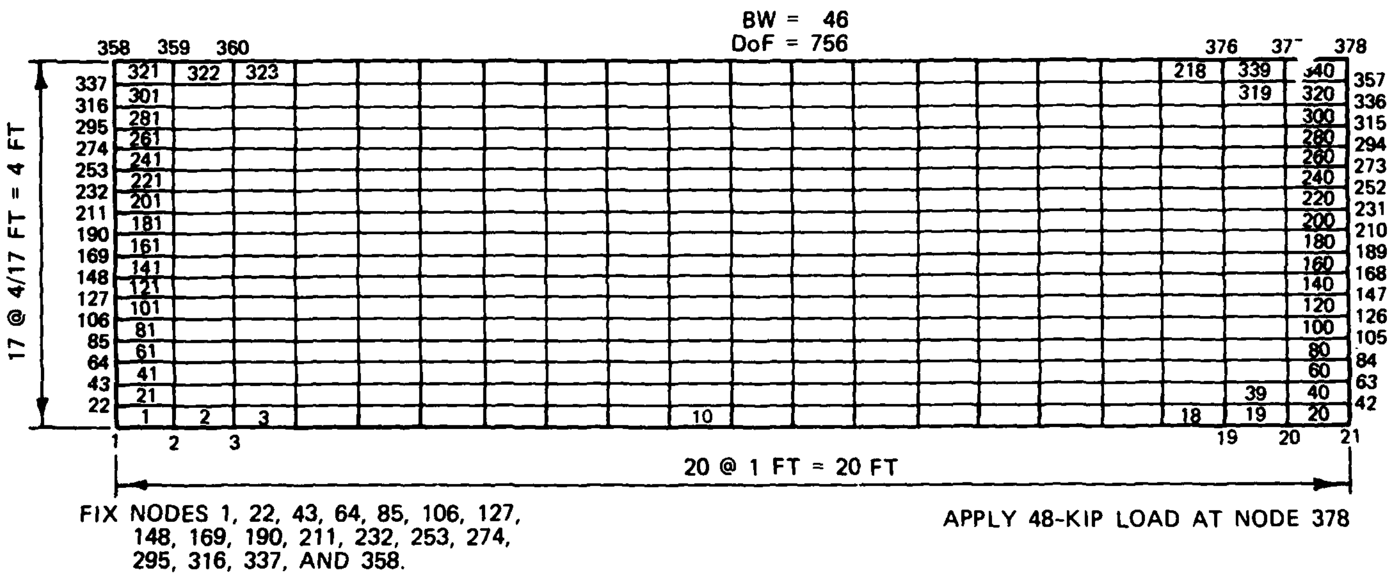

Figure 5. Grid Id

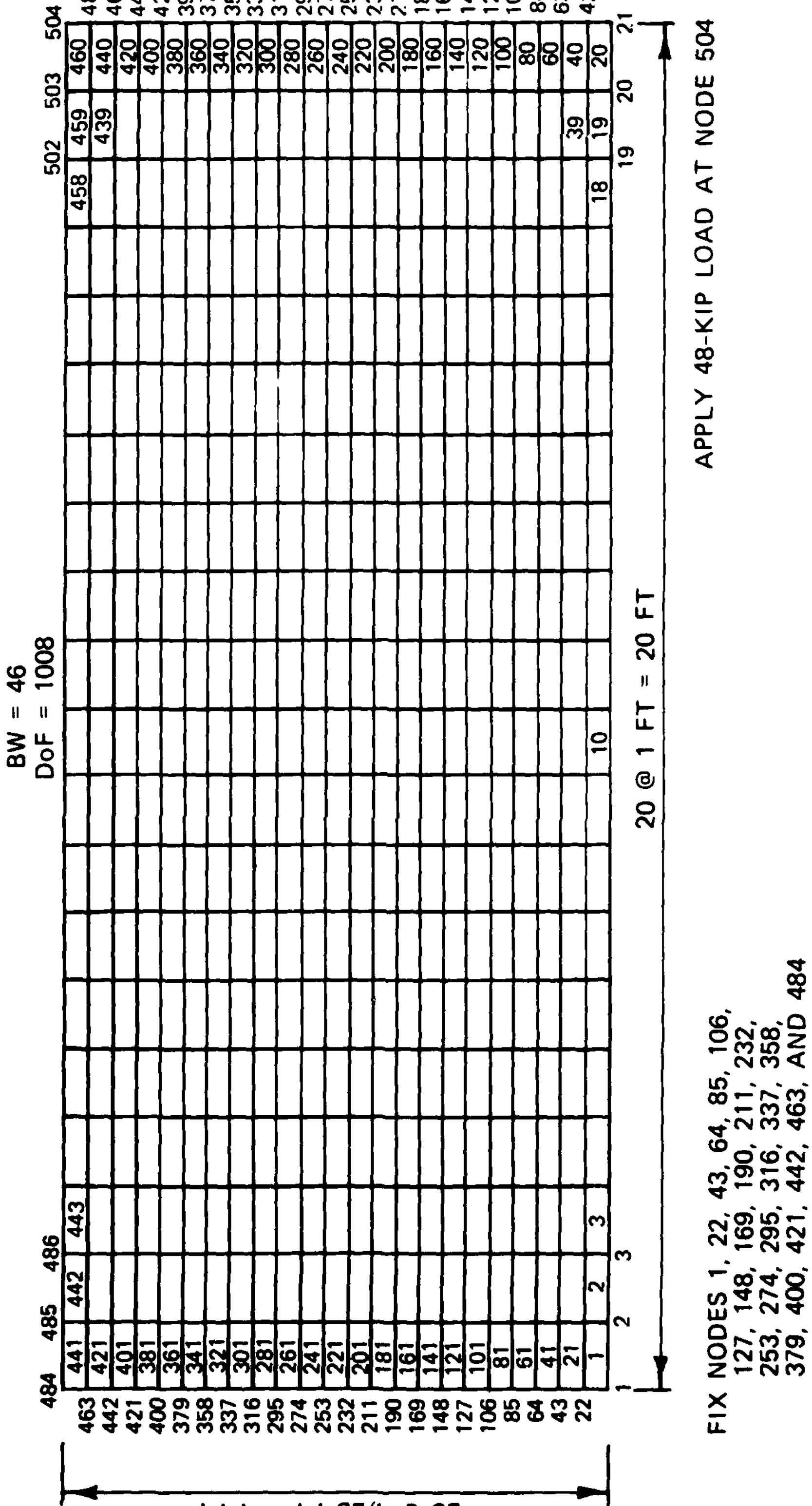

Figure 6. Grid Ie

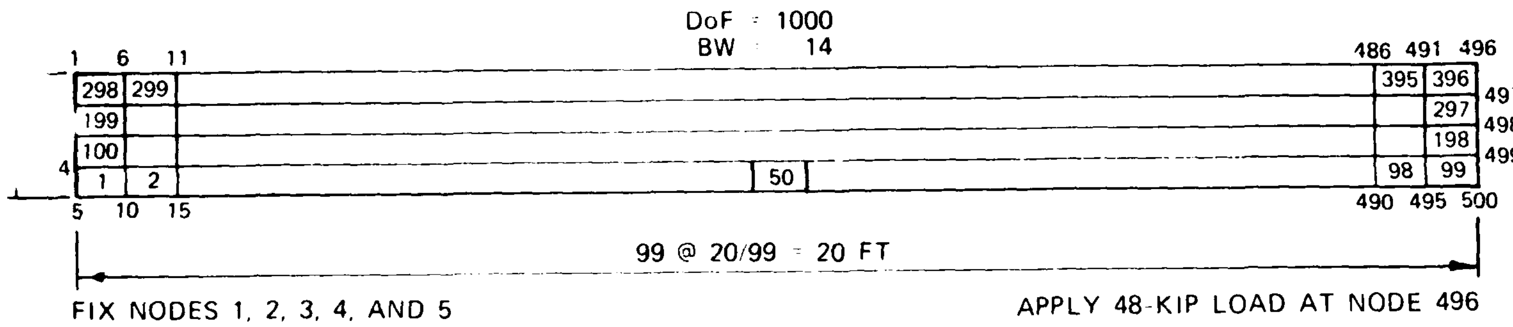

Figure 7. Grid IIa

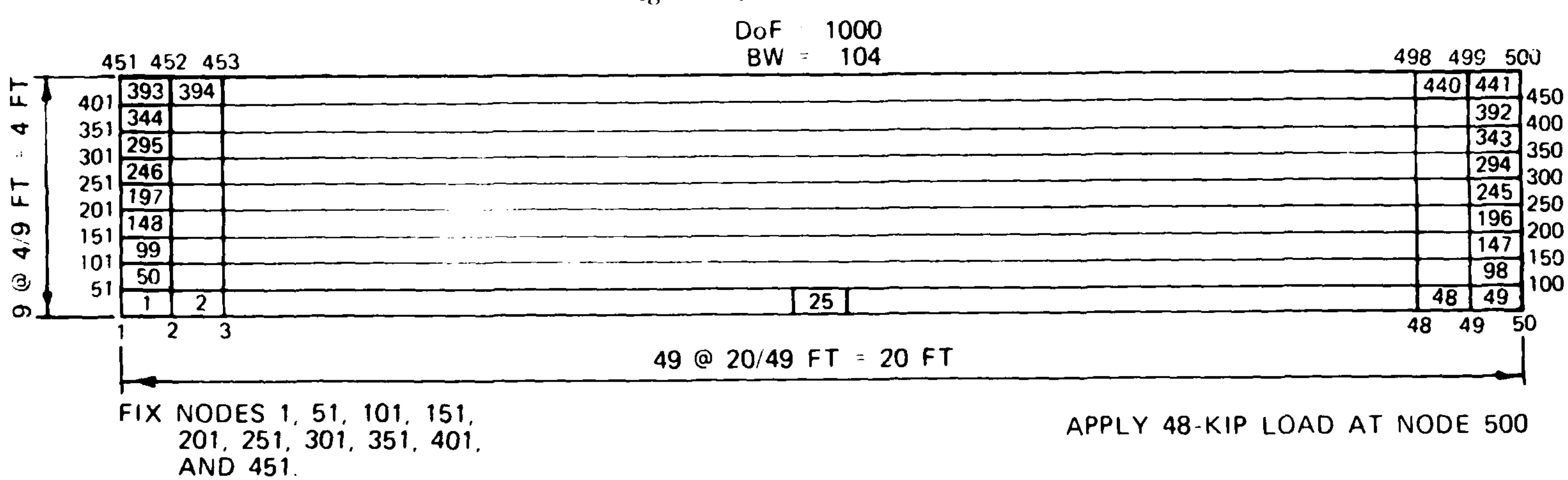

Figure 8. Grid IIb

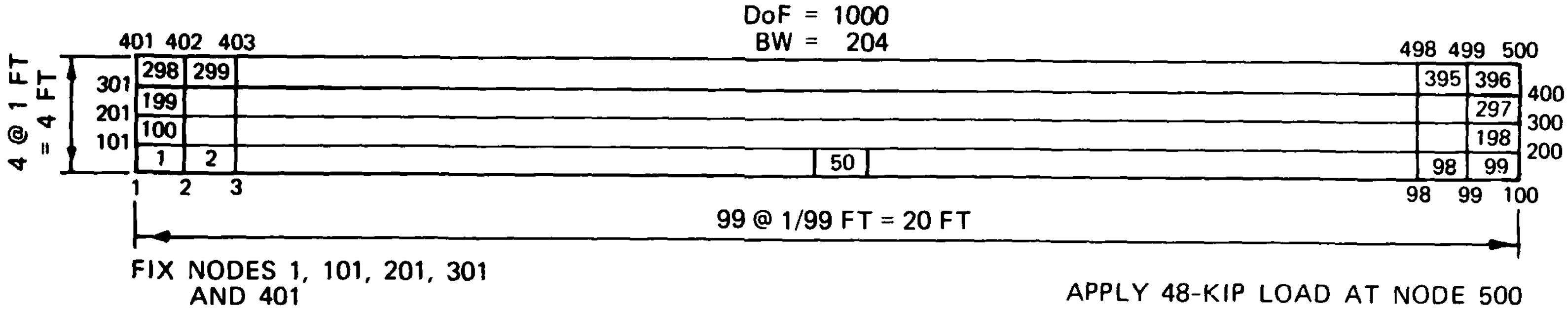

Figure 9. Grid IIc

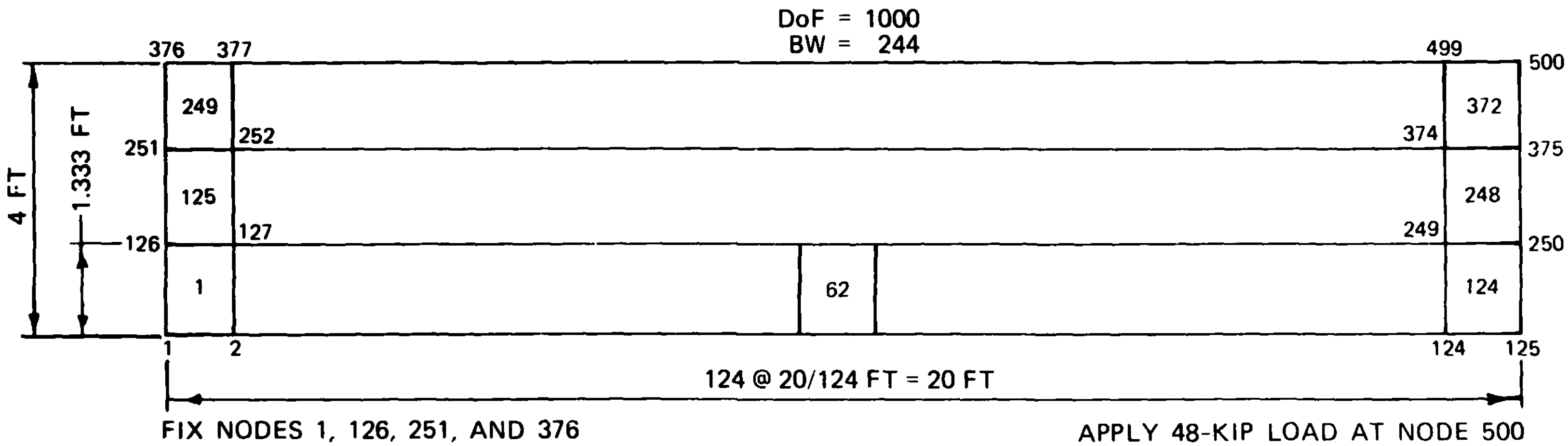

Figure 10. Grid IId

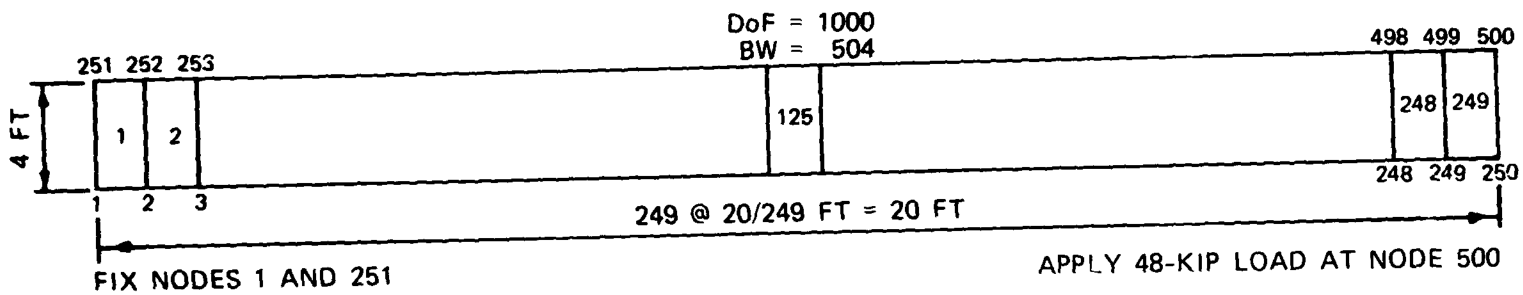

Figure 11. Grid IIe

Results

18. End deflections and some schemes for each grid from the SAP run are presented in Table 1. The other five GPP's produced comparable results. The results given by grid IIa are the closest to the theoretical solution determined using the theory of elasticity. The grid IIa aspect ratio was closest to one and had the most DoF's, except for grid Ie. Convergence of a FE analysis to the correct solution can be checked only by rerunning the problem with a finer grid that contains the coarser grid. If results from the finer grid match the results from the coarse grid, the problem has converged. However, if the results do not match, the finer grid must be further refined.

19. Tables 2 and 3 compare the costs of running the problems using the six GPP's. Some of the results from ANSYS and SUPERB are not shown because they use a wavefront solution routine. Table 2 shows costs of each run for each GPP for a 4-hour turnaround, while Table 3 provides costs for delayed processing. Figure 12 shows the effect of changing the DoF's on cost; Figure 13 shows the variation of cost with BW for each GPP for a 4-hour turnaround. Figures 14 and 15 give the corresponding plots for delayed processing. These figures indicate the effects that changing BW's and DoF's have on the cost of a FE problem. These figures are also valid for comparing differences in cost for these problems. However, the figures are not valid for projecting exact costs of other runs, though they can serve for making rough estimates. One of the most frequent complaints about GPP's concerns the lack of good estimates for time and cost for different analyses (Fong 1982).

Analysis of results

20. As can be seen from the data, regardless of the GPP, the user must keep the BW as small as possible and provide sufficient nodes to actually model the problem. BW can be minimized using BW minimization routines that are available in all the GPP's evaluated. SUPERB and ANSYS use a wave front procedure for solving the simultaneous equations. In this procedure, the cost of running a problem is not dependent on the BW but on the numbering of the elements.

Comparisons for Two "Real World" Problems

21. Two "real world" problems (for a concrete lock wall monolith and a steel bulkhead) were also chosen for comparison. These problems are illustrated in Figures 16 and 17. A FE grid for each problem was generated and

Table 1

Displacements and Centroidal Stresses for a 20-ft Cantilever Beam from WES SAP

			Displacement*			Centroidal Stresses		
Grid	BW	DoF's	Node No.	ft	Element No.	S_{xx}, ksf	S_{yy}, ksf	S_{xy}, ksf
Ia	46	84	21	-0.0507462	10	-0.4379×10^{-13}	-0.4349×10^{-5}	-12.00
Ib	46	252	21	-0.0552697	10	-147.1	-0.1654×10^{-3}	-6.397
Ic	46	504	21	-0.0554772	10	-167.6	0.3176×10^{-4}	-3.294
Id	46	756	21	-0.0555095	10	-173.7	-0.7470×10^{-4}	-2.269
Ie	46	1008	21	-0.0555201	10	-176.5	0.9945×10^{-4}	-1.768
IIa	14	1000	500	-0.0567140	50	-134.0	-0.5409×10^{-3}	-7.531
IIb	104	1000	50	-0.0566299	25	-159.2	-0.1293×10^{-3}	-3.746
IIc	204	1000	100	-0.0564596	50	-134.0	-0.5378×10^{-3}	-7.531
IId	254	1000	125	-0.0554322	62	-118.2	-0.2396×10^{-3}	-9.249
IIe	504	1000	250	-0.0518389	125	-0.1948×10^{-10}	-0.2855×10^{-4}	-12.00

* Theoretical results: Displacement $= \frac{PL^3}{3EI} + \frac{Pc^2L}{2IG} = -0.05772$ ft; P = 48 kips, L = 20 ft, $E = 3 \times 10^6$ psi, $I = 110592$ in.^{4}, c = 24 in., $G = 1.154 \times 10^6$ psi.

Table 2

Costs ($'s) of Runs for 4-Hr Turnaround for Cantilever Beam Analysis

Grid			GTSTRUDL*		MCAUTO STRUDL**			E^3SAP*		SUPERB†		SAP††		ANSYS*	
No.	DoF's	BW	BU	Cost	BU	FEEU	Cost	BU	Cost	BU	Cost	BU	Cost	BU	Cost
Ia	84	46	72.180	3.68	1.20	15	5.67	27.663	1.41	161.9	16.19	458	13.74	52.245	2.66
b	252	46	213.810	10.90	3.49	78	18.76	79.968	4.08	347.3	34.73	606	18.18	132.863	6.78
c	504	46	414.094	21.12	7.66	202	43.21	156.437	7.98	711.9	71.19	878	26.34	257.210	13.12
d	756	46	856.042	43.66	11.78	347	68.84	237.646	12.12	1046.0	104.60	1,102	33.06	380.951	19.43
e	1008	46	1450.867	73.99	16.02	508	96.00	320.880	16.36	1387.0	138.70	1,348	40.44	508.309	25.92
IIa	1000	14	1056.780	53.90	14.82	473	89.02	250.667	12.78	‡	‡	1,072	32.16	455.272	23.22
b	1000	104	1649.971	84.15	20.07	495	110.94	386.031	19.69	1847.9	184.79	2,200	66.00	615.331	31.38
c	1000	204	2216.267	113.03	33.68	473	162.57	622.83	31.76	3836.2	383.62	4,504	135.12	818.221	41.73
d	1000	254	2520.349	128.54	43.96	461	201.87	1051.252	53.61	‡‡	‡‡	6,389	191.67	913.118	46.57
e	1000	504	6490.22	331.00	101.33	402	421.72	1929.605	98.41	‡	‡	26,812	804.06	‡	‡

Note: BU = Billing unit used as indication of computer measures used.
FEEU = Service charge for use of MCAUTO STRUDL.
* Boeing priority 4: $0.085/BU - 40% discount.
** MCAUTO: $6.50/BU + $0.11/FEEU - 40% discount.
† INFONET: $0.10/BU.
†† WES primetime: $0.3/BU.
‡ Results were not obtained for wave front equal to bandwidth.
‡‡ Not analyzed.

Table 3

Costs ($'s) of Delayed Processing Runs for Cantilever Beam Analysis

	Grid		GTSTRUDL*		MCAUTO STRUDL**			E^3SAP*		SUPERB†		SAP††		ANSYS*	
No.	DoF's	BW	BU	Cost	BU	FEEU	Cost	BU	Cost	BU	Cost	BU	Cost	BU	Cost
Ia	84	46	77.180	2.78	1.20	15	3.51	27.663	1.00	161.9	4.86	458	8.24	52.245	1.88
b	252	46	213.810	7.70	3.49	78	12.47	79.968	2.88	347.3	10.42	606	10.91	132.863	4.78
c	504	46	414.094	14.91	7.66	202	29.42	156.437	5.63	711.9	21.36	878	15.80	251.210	9.26
d	756	46	856.042	30.82	11.78	347	47.64	237.646	8.56	1046.0	31.38	1,102	19.84	380.951	13.71
e	1008	46	1450.867	52.23	16.02	508	67.17	320.880	11.55	1387.0	41.61	1,348	24.26	508.309	18.30
IIa	1000	14	1056.780	38.04	14.82	473	62.34	250.667	9.02	‡	‡	1,041	18.74	455.272	16.39
b	1000	104	1649.971	59.40	20.07	495	74.81	386.031	13.90	1847.9	55.44	2,107	37.93	615.331	22.15
c	1000	204	2216.267	79.79	33.68	473	101.95	622.83	22.42	3836.2	115.09	5,080	91.44	818.221	29.46
d	1000	254	2520.349	90.73	43.96	461	122.74	1051.252	37.85	‡‡	‡‡	6,389	115.00	913.118	32.87
e	1000	504	6440.020	233.65	101.33	402	239.33	1929.605	69.47	‡	‡	26,812	482.44	‡	‡

* Boeing priority 1: $0.06/BU - 40% discount.
** MCAUTO deferred run: $3.50/BU + 0.11/FEEU - 40% discount.
† INFONET priority 1: $0.03/BU.
†† WES non-primetime: 0.6 × $0.03/BU.
‡ Results were not obtained for wave front equal to desired bandwidth.
‡‡ Not analyzed.

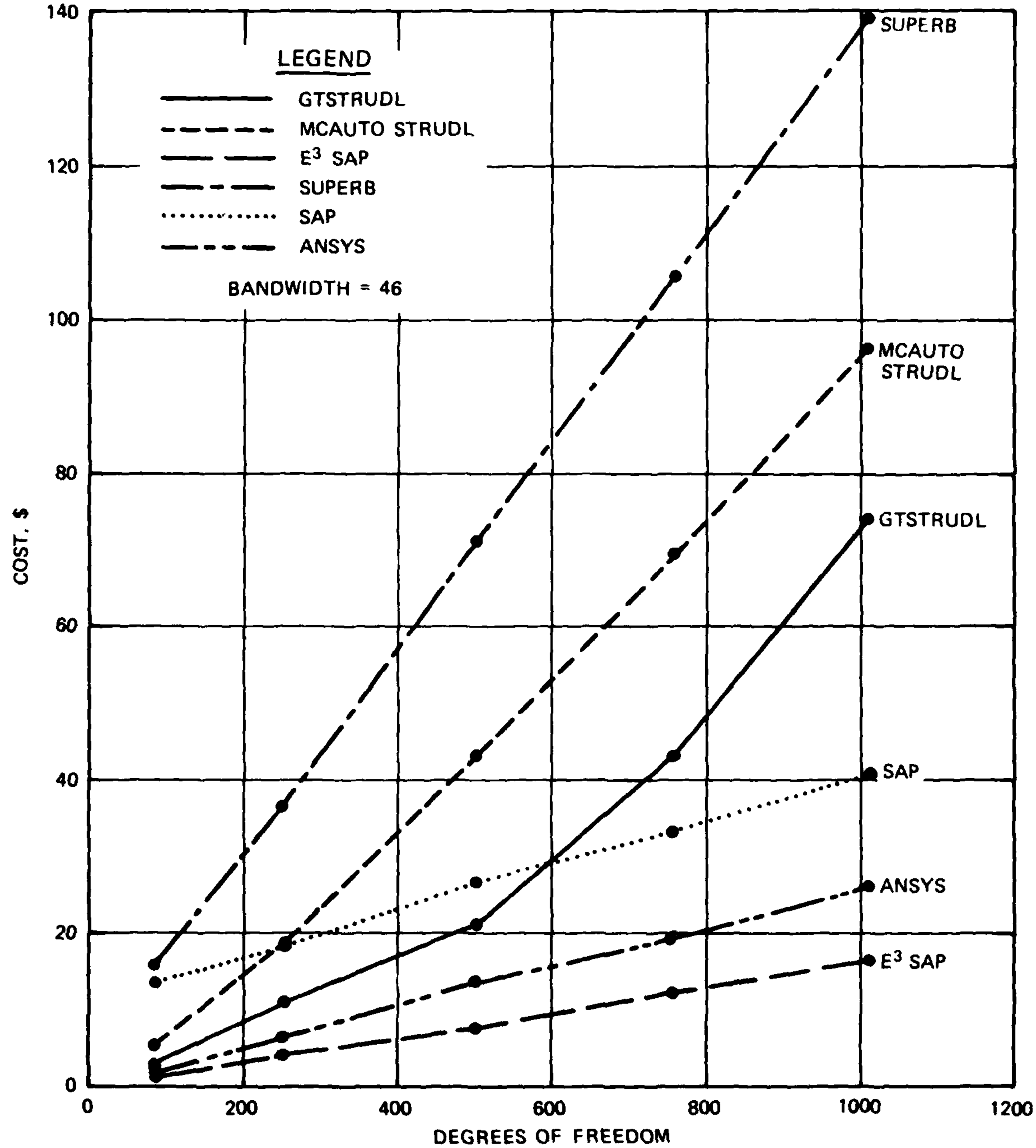

Figure 12. Effects of varying DoF's on cost for a 4-hr turnaround

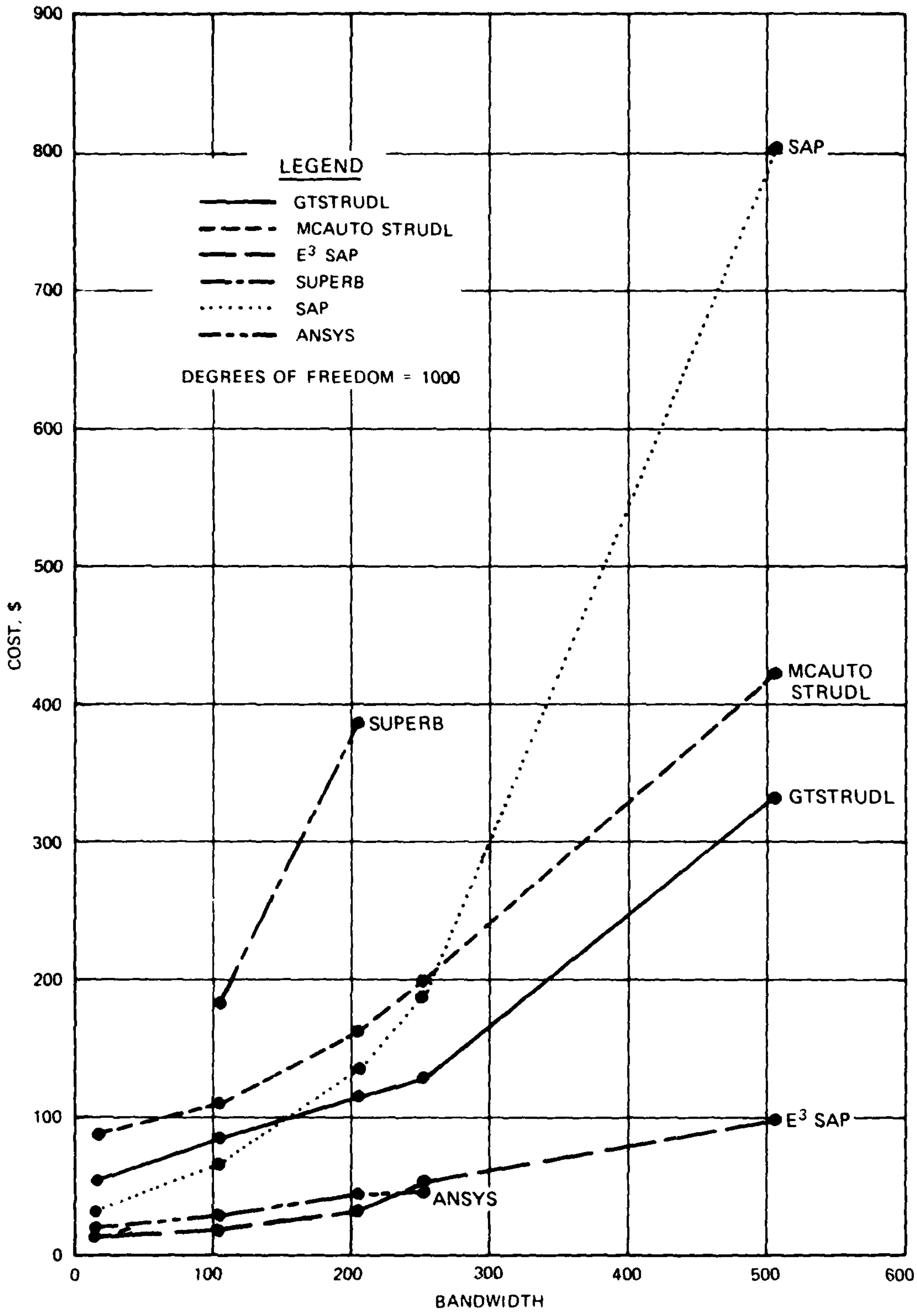

Figure 13. Effects of varying BW on cost for a 4-hour turnaround

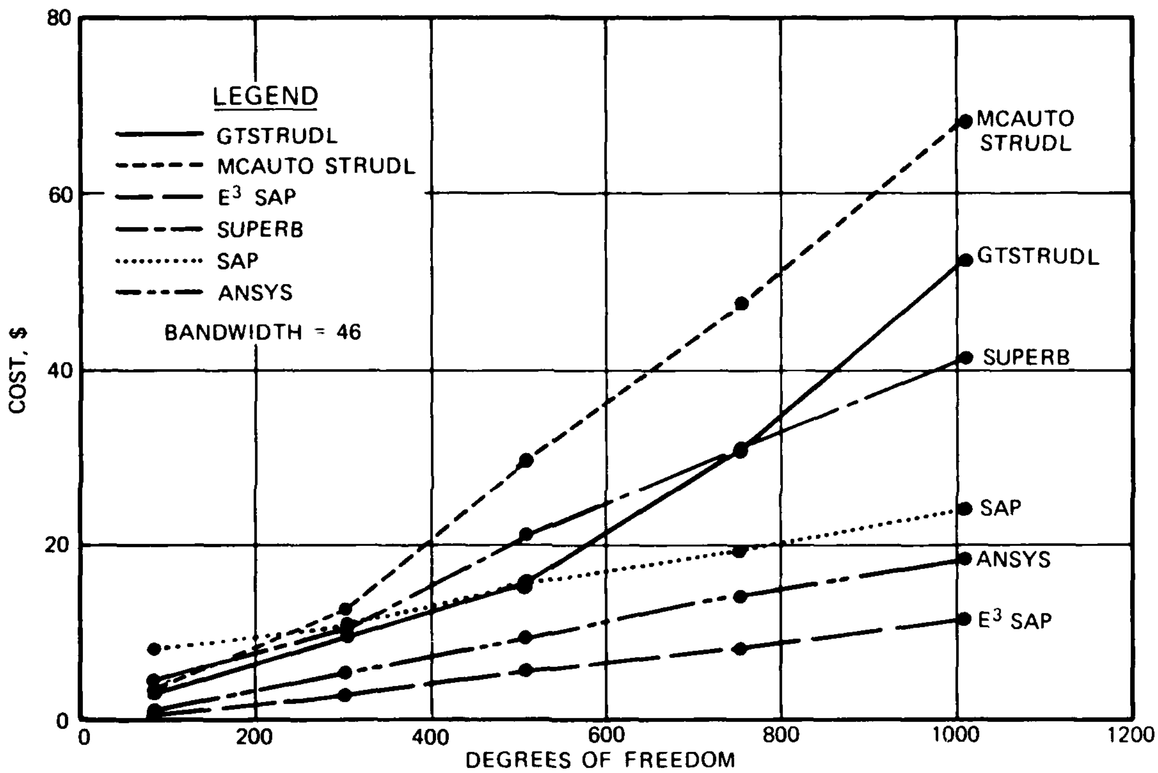

Figure 14. Effects of varying DoF's on cost for delayed processing

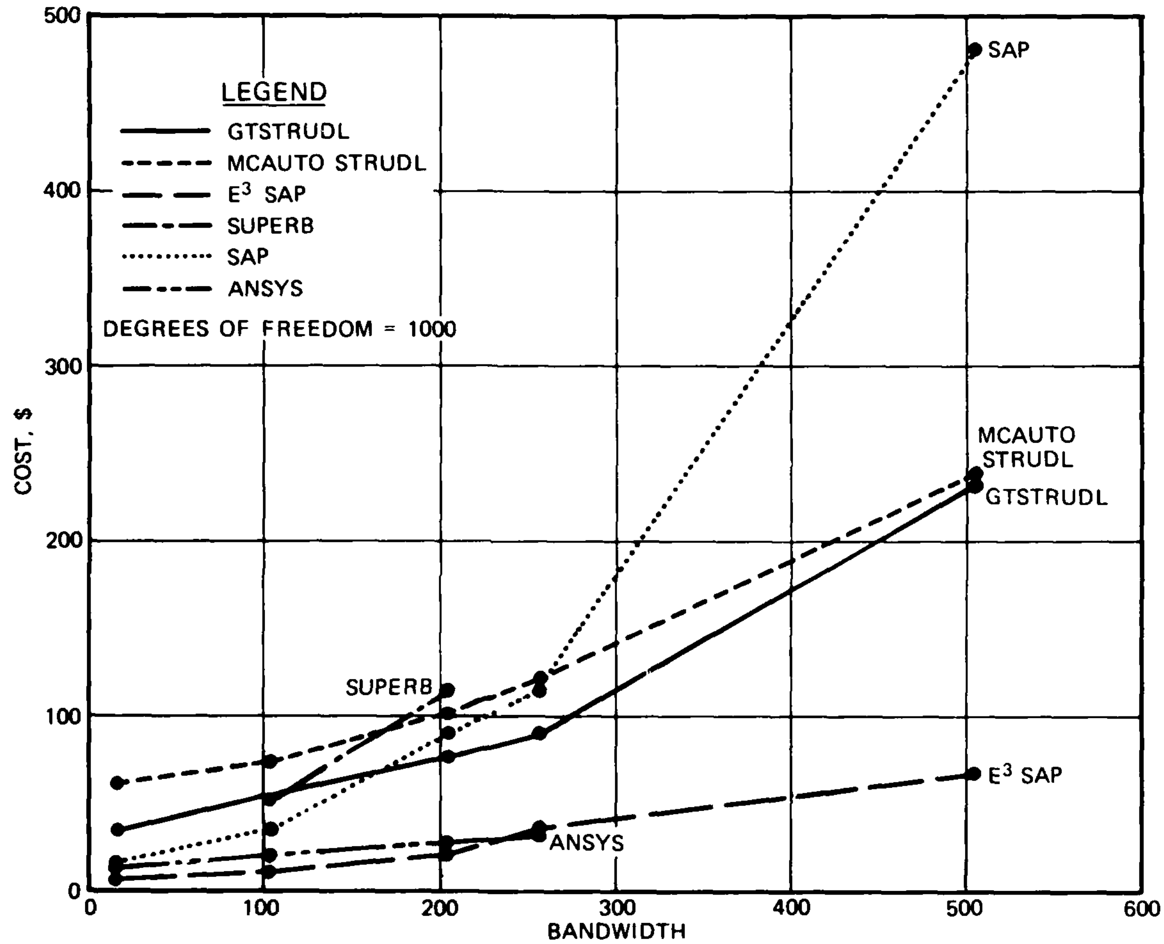

Figure 15. Effects of varying BW on cost for delayed processing

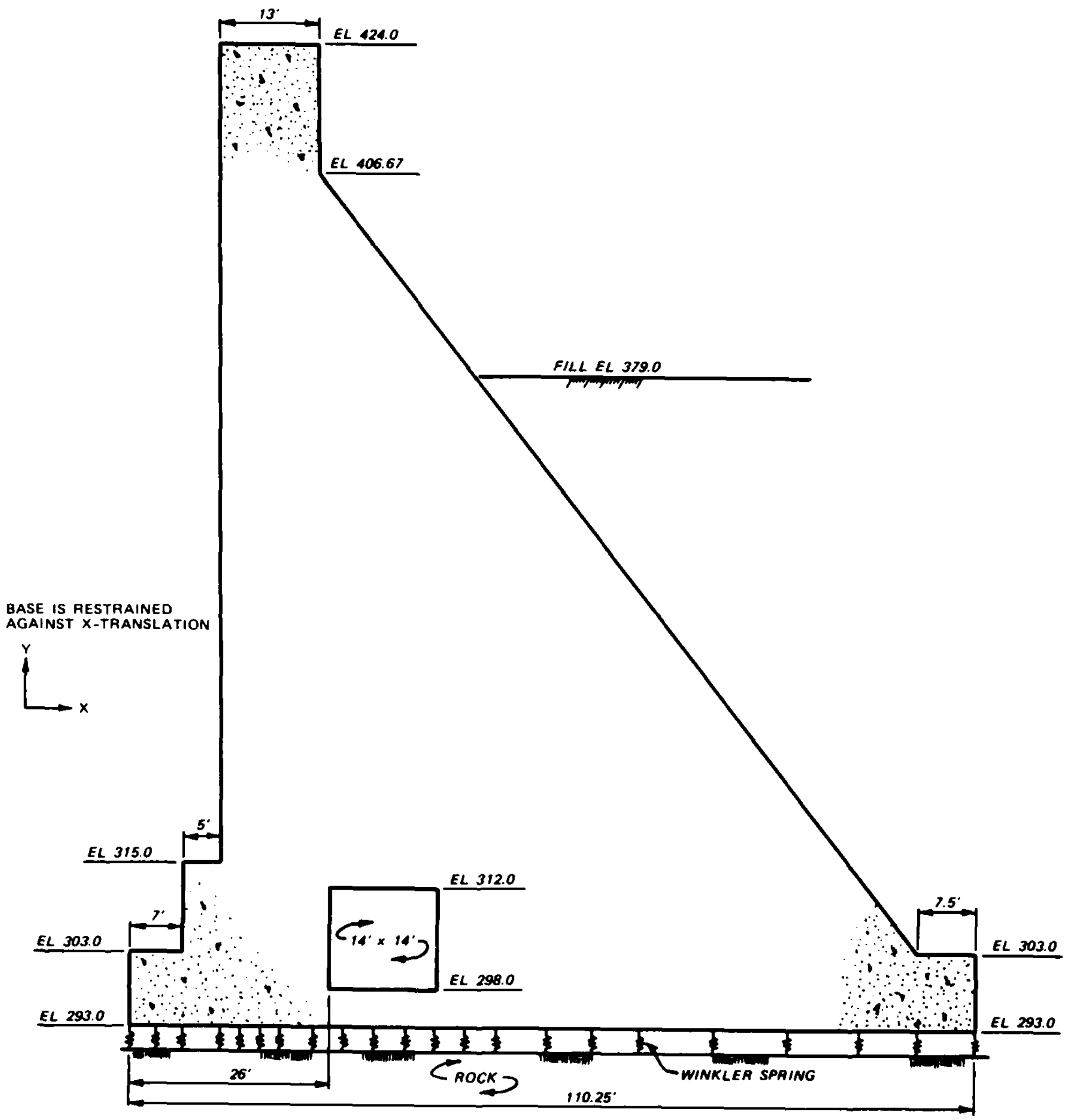

Figure 16. Lock wall problem

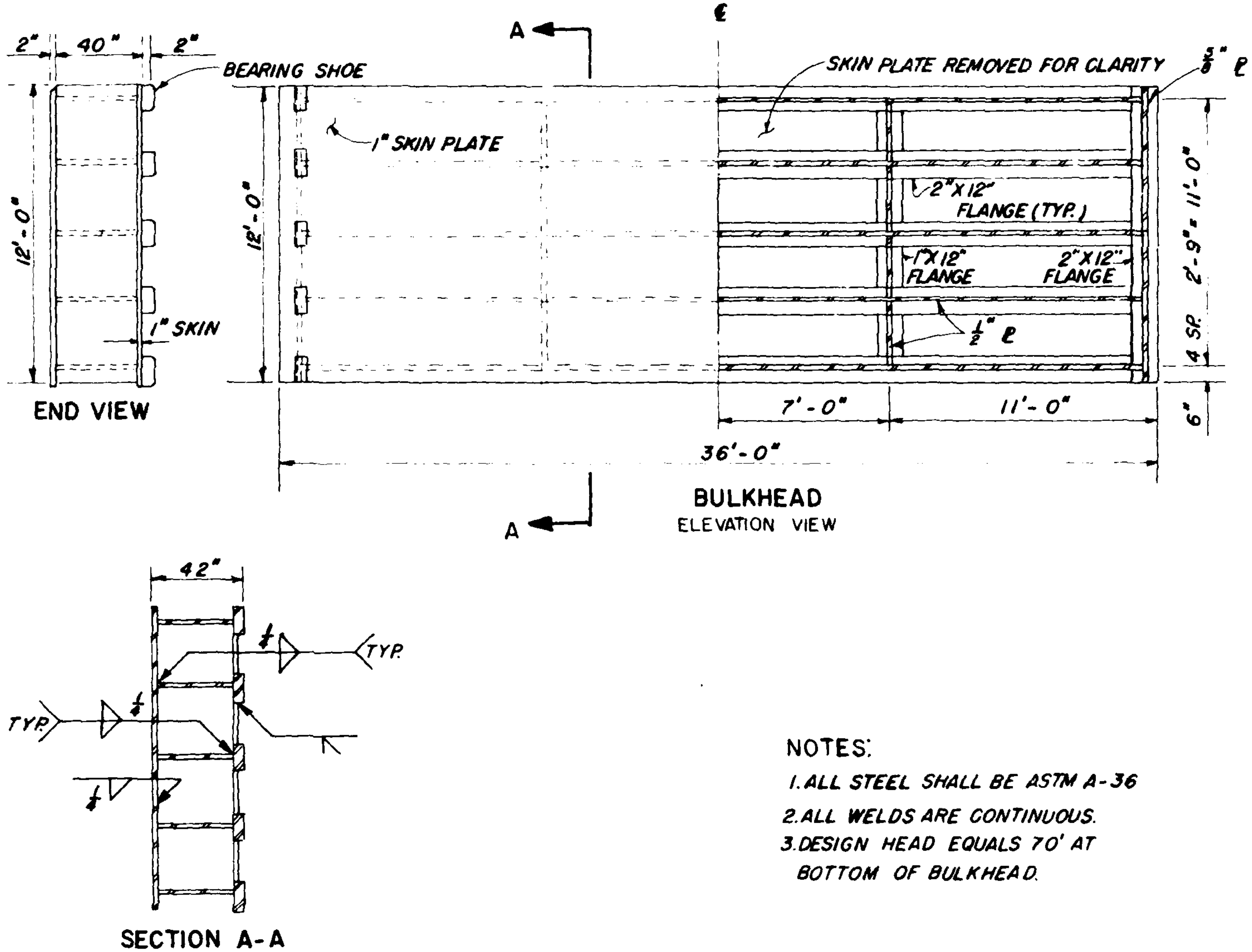

Figure 17. Bulkhead problem

given to each member of the CASE Task Group on Finite Element Analysis. Each task group member then converted the general FE data into specific data for a particular GPP. After proper conversion, two FE problems were run using each of the six GPP's. Each task group member worked on his problem as if it were a current design project. This resulted in a variety of procedures for pre- and post-processing of the runs and selection of different element types depending on the individual running the problem as well as the chosen GPP.

22. The lock wall monolith was assumed to be of one material type and to be acting on a Winkler foundation. The lock wall was modeled using 384 nodes and 313 isoparametric elements (Ergatoudis, Irons, and Zienkiewicz 1968; Aparicia and Connor 1970; Connor and Will 1969) having a BW of 82 (Figure 18). The foundation was modeled by 19 springs. The bulkhead consisted of a steel skinplate with horizontal and vertical beams. It was modeled by 129 beam members (three different geometric properties) and 360 plate FE's. The grid contained 406 nodal points with a BW of 113 (Figure 19). Documentation for these two problems according to ETL 1110-2-254 is provided in Appendices B and C.

Pre- and post-processing

23. Pre-processing was limited to the very minimum but included a plot of the entire grid. Checks on boundary conditions, loads, and window plots of the dense portion of the grid were also completed before analysis. Appendix D presents the plot activity and corresponding costs for pre- and post-processor runs with each GPP.

Selection of elements

24. Each GPP has a different element library, and selection of the proper element(s) for a problem that could simulate real behavior is important. For the lock wall problem, the choice was easy: an identical plane strain element was available on all six GPP's. For the bulkhead problem, however, the selection was not so easy because modeling the skin plate involved use of a plate stretching and bending element. The pure plate bending problem requires a minimum of 3 DoF's: an out-of-plane displacement, and two out-of-plane rotations. This, combined with the two in-plane translations, produces 5 DoF's for this element. The element selected for the problem could be either the conventional element, where compatibility of selected displacements would be maintained, or a hybrid element, where compatibility would be maintained by selected displacements and stresses. Appendix E lists the elements used with each of the GPP's for each problem.

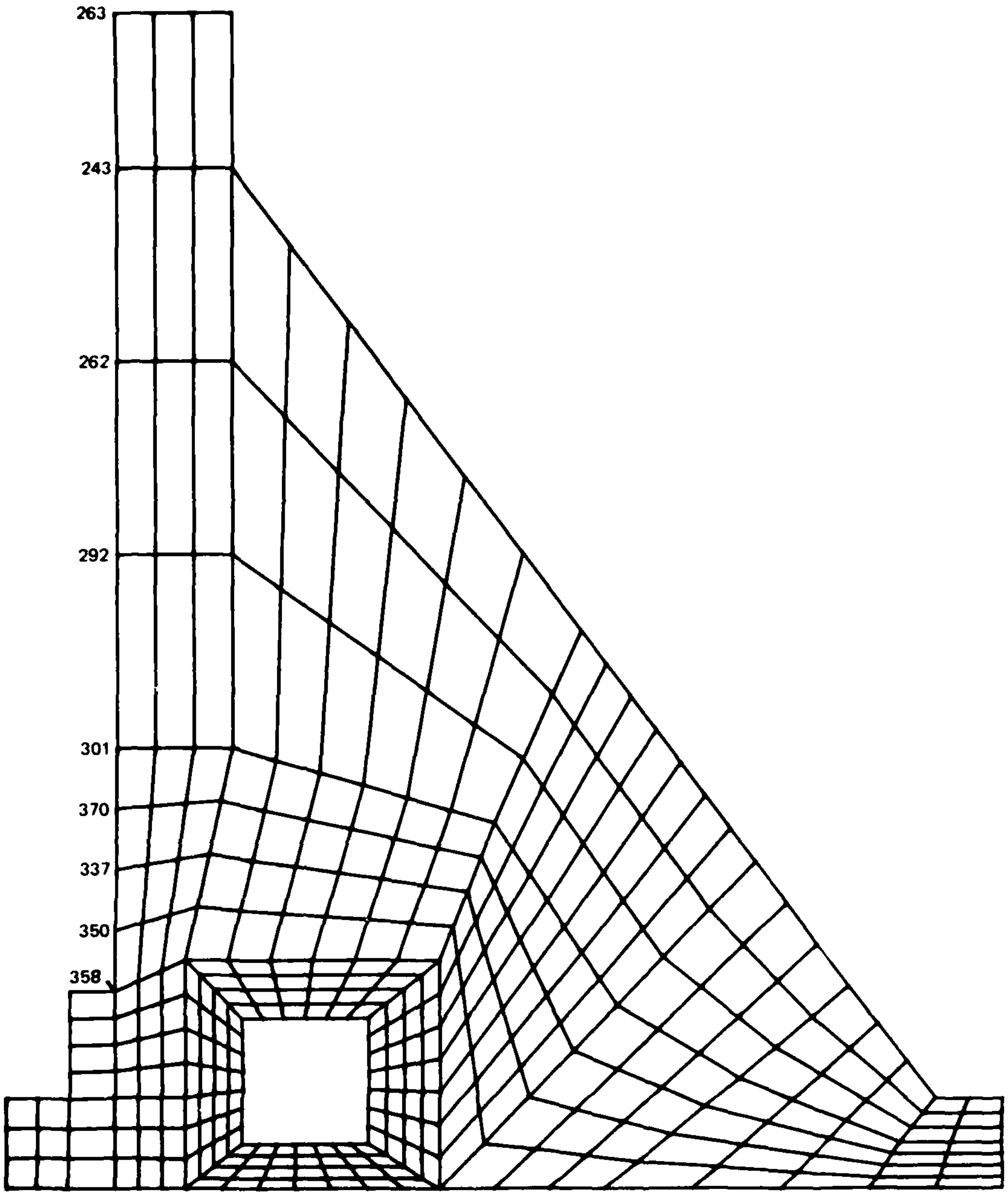

Figure 18. Grid for lock wall problem

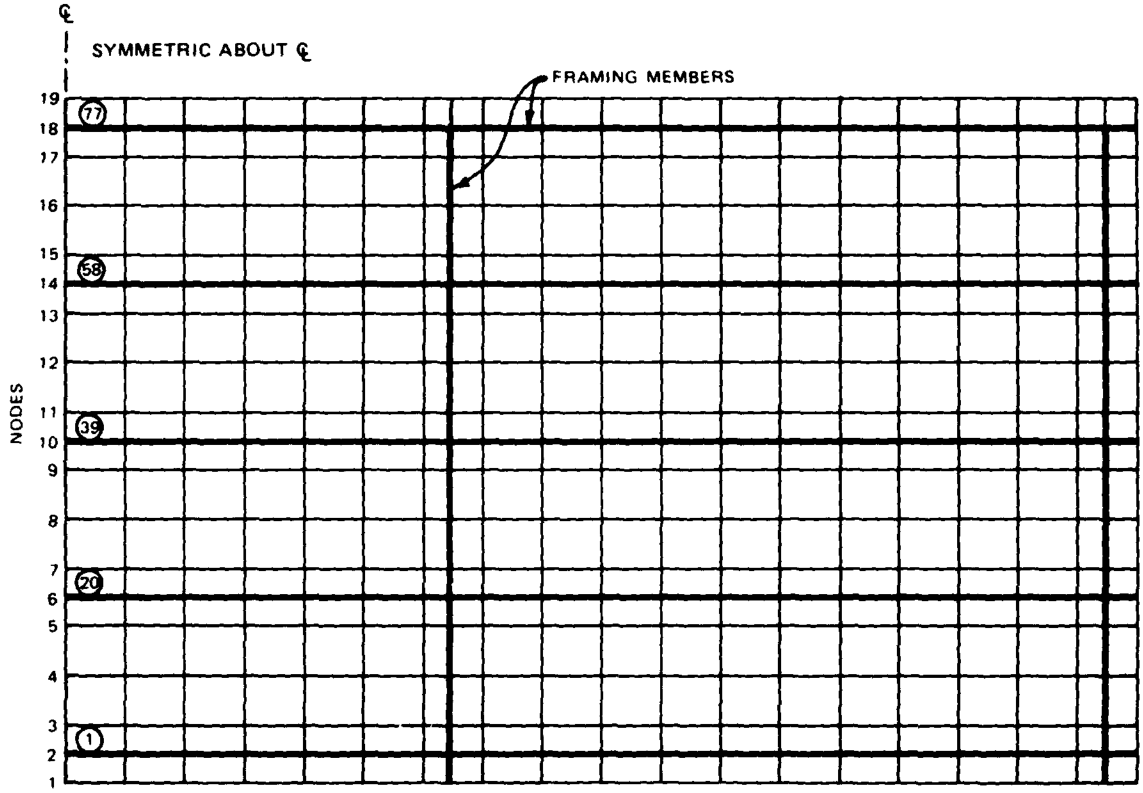

Figure 19. Grid for bulkhead problem

Results

25. Table 4 lists the displacements of the inside face of the lock wall, while Table 5 lists the displacements of the left-hand side of the bulkhead. The slight differences could have been caused by:

   a. Round-off or truncation errors in the computations due to different word-length computer.

   b. Use of different elements.

or a combination of these factors. Figures 20-27 display typical results from the FE solutions. Figure 20 shows the displacement of the lock wall. Figure 21 shows the contours of the σ_x stresses, while Figure 23 displays the σ_y stresses for the lock wall problem. Figures 25-27 give the corresponding output for the bulkhead problems.

Costs

26. The costs of analyzing the two problems are shown in Table 6. The cost variation is due not only to using GPP's with different capabilities, but also due to using different computers. It should be noted that these costs may not be the minimum cost of using a given computer service but do reflect the cost of solving this class of problem.

Time required

27. There was not a significant difference in man-hours required to complete either problem. After the grids were obtained, it took 4 to 5 days for converting data to the specific GPP, pre-processing, analysis, and post-processing. Each activity required only 2 to 3 hours to complete if no mistakes were made. However, due to the complexity of the problems, it is reasonable to assume that an engineer working on such a problem would be likely to make some mistakes and consequently his required time could double or triple.

Selection of GPP

28. Cost should be only one of many factors used in selecting a GPP. In addition to the guidelines listed in paragraph 6, the following questions should be addressed:

   a. What elements are required to model the problem?

   b. What boundary conditions are needed?

   c. What loading conditions are needed?

Table 4

Lock Wall Displacements

Node	Lateral Displacement, in., as Determined by Cited Program					
	GTSTRUDL	MCAUTO STRUDL	E^3SAP	SAP	ANSYS	SUPERB
263	-0.002495	-0.002491	-0.002495	-0.002495	-0.002502	-0.002495
243	-0.001977	-0.001971	-0.001977	-0.001977	-0.001983	-0.001977
262	-0.001403	-0.001396	-0.001403	-0.001403	-0.001407	-0.001403
282	-0.0009694	-0.0009629	-0.0009694	-0.0009694	-0.0009720	-0.0009694
301	-0.0006619	-0.0006575	-0.0006619	-0.0006619	-0.0006630	-0.0006619
320	-0.0005821	-0.0005785	-0.0005822	-0.0005822	-0.0005827	-0.0005822
337	-0.0005047	-0.0005019	-0.0005047	-0.0005047	-0.0005046	-0.0005046
350	-0.0004360	-0.0004339	-0.0004360	-0.0004360	-0.0004350	-0.0004359
358	-0.0003384	-0.0003371	-0.0003384	-0.0003384	-0.0003358	-0.0003384

Table 5

Bulkhead Displacement and Flange Stresses

Node	Lateral Displacement, in., as Determined by Cited Program					
	GTSTRUDL	MCAUTO	E^3SAP	ANSYS	SAP	SUPERB
1	-0.3317	-0.3314	-0.3355	-0.3318	-0.3355	-0.3359
2	-0.3654	-0.3647	-0.3647	-0.3654	-0.3647	-0.3640
3	-0.4039	-0.4045	-0.3990	-0.4038	-0.3990	-0.3936
4	-0.4370	-0.4371	-0.4286	-0.4369	-0.4286	-0.4321
5	-0.4019	-0.4009	-0.3980	-0.4018	-0.3980	-0.4094
6	-0.3811	-0.3801	-0.3795	-0.3811	-0.3795	-0.3811
7	-0.3877	-0.3889	-0.3853	-0.3877	-0.3853	-0.3896
8	-0.4060	-0.4070	-0.4011	-0.4060	-0.4011	-0.4042
9	-0.3834	-0.3828	-0.3808	-0.3833	-0.3808	-0.3888
10	-0.3696	-0.3687	-0.3683	-0.3696	-0.3683	-0.3700
11	-0.3775	-0.3784	-0.3750	-0.3775	-0.3750	-0.3778
12	-0.3911	-0.3918	-0.3863	-0.3911	-0.3863	-0.3905
13	-0.3653	-0.3646	-0.3630	-0.3653	-0.3630	-0.3646
14	-0.3532	-0.3523	-0.3517	-0.3531	-0.3517	-0.3559
15	-0.3657	-0.3668	-0.3623	-0.3657	-0.3623	-0.3628
16	-0.3879	-0.3891	-0.3808	-0.3878	-0.3808	-0.3824
17	-0.3521	-0.3518	-0.3480	-0.3520	-0.3480	-0.3550
18	-0.3149	-0.3143	-0.3143	-0.3149	-0.3143	-0.3162
19	-0.2818	-0.2818	-0.2850	-0.2818	-0.2850	-0.2816

Beam	Flange Beam Element Stress, ksi, as Determined by Cited Program					
	GTSTRUDL	MCAUTO	E^3SAP	ANSYS	SAP	SUPERB
1	18.53	18.55	18.86	18.53	18.86	18.82
20	17.21	17.20	17.01	17.22	17.01	17.13
39	16.64	16.63	16.40	16.64	16.40	16.38
58	15.93	15.93	15.78	15.99	15.78	15.82
77	15.96	15.98	16.27	15.95	16.27	16.17

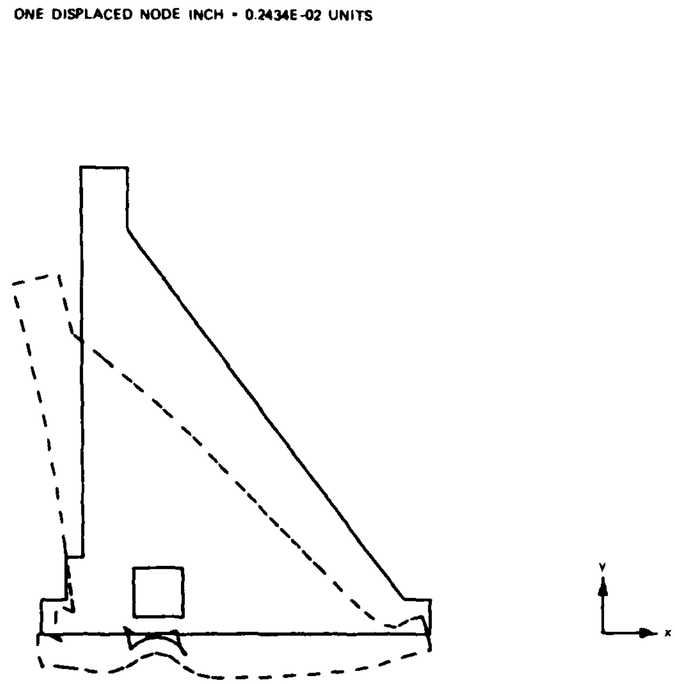

Figure 20. Displacement plot for lock wall problem

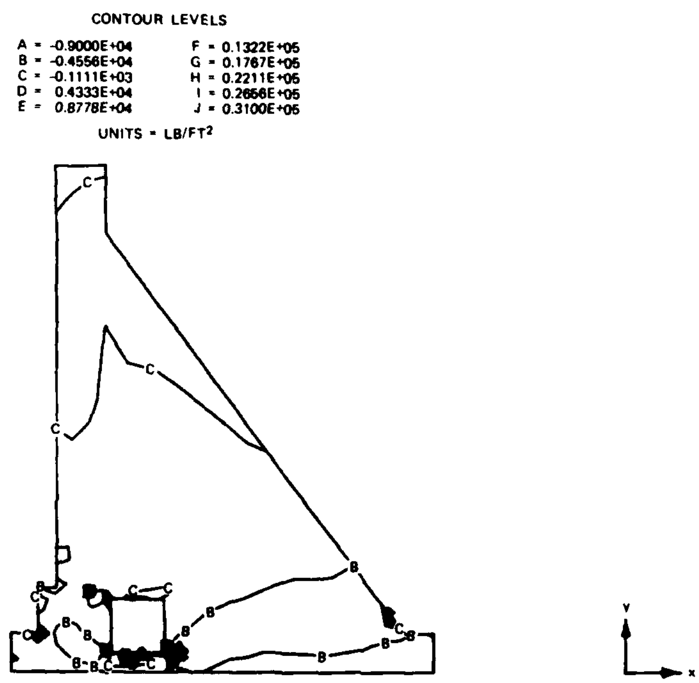

Figure 21. σ_x stress plot for lock wall problem

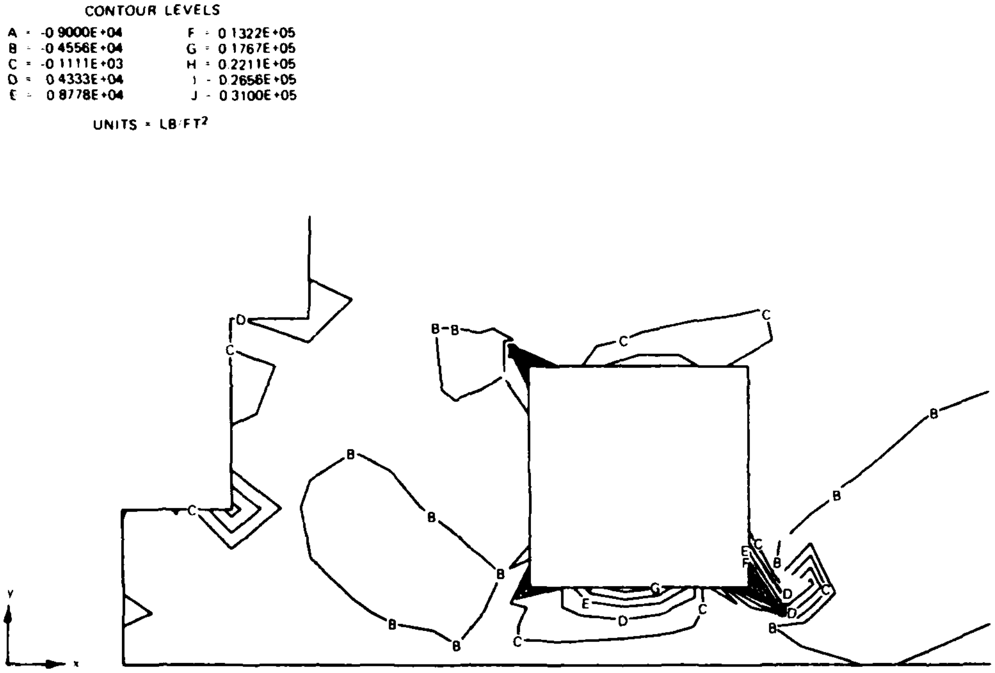

Figure 22. Window plot of σ_x stresses for lock wall problem

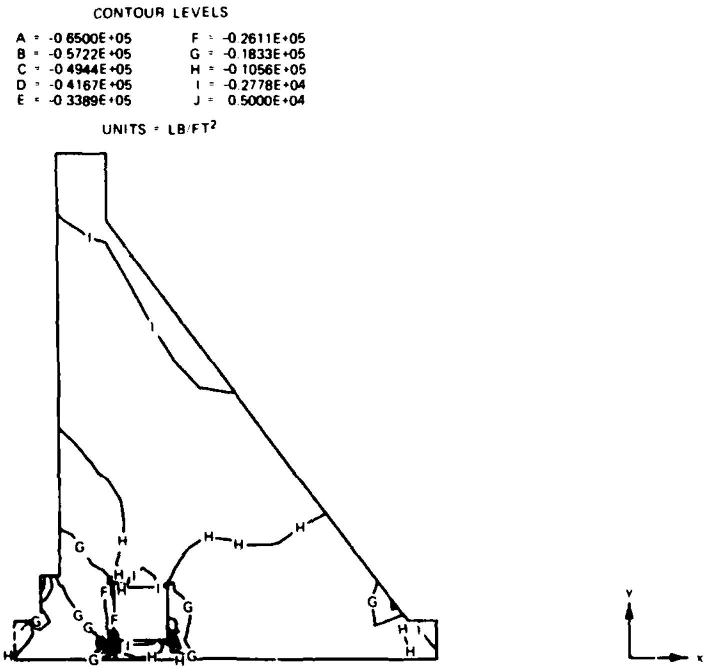

Figure 23. σ_y stress plot for lock wall problem

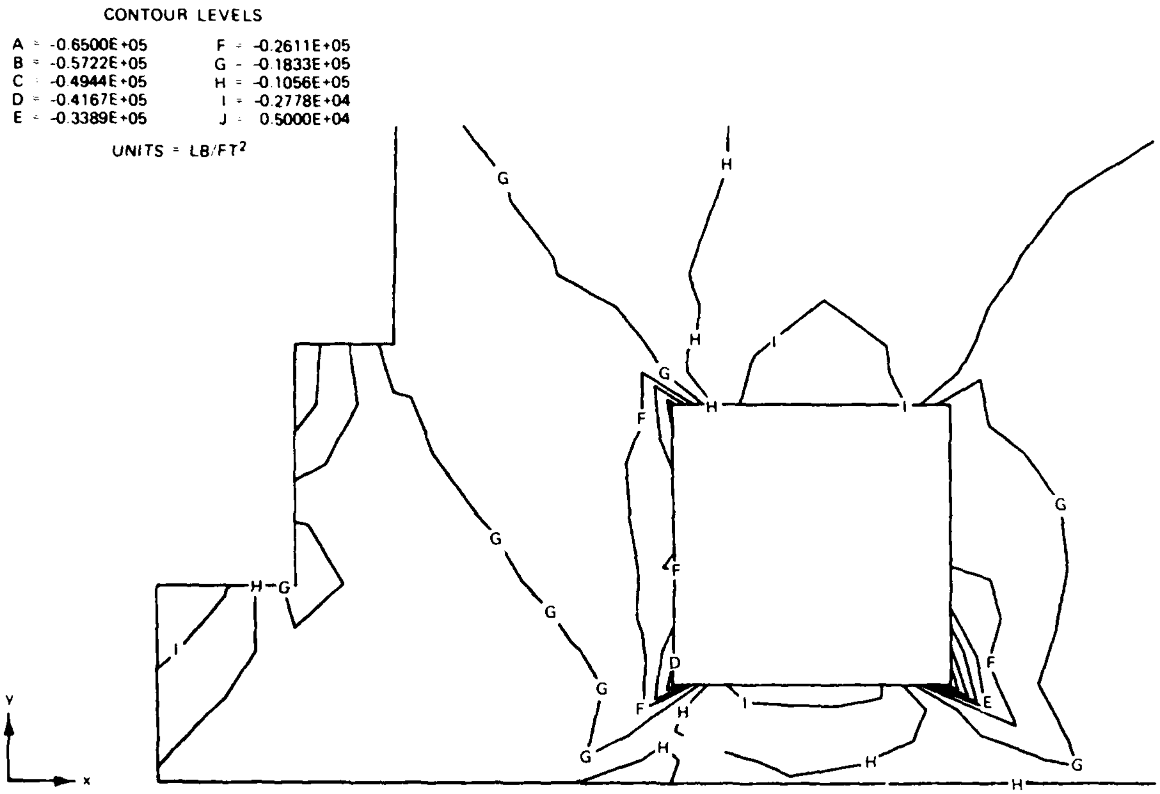

Figure 24. Window plot of σ_y stresses from lock wall problem

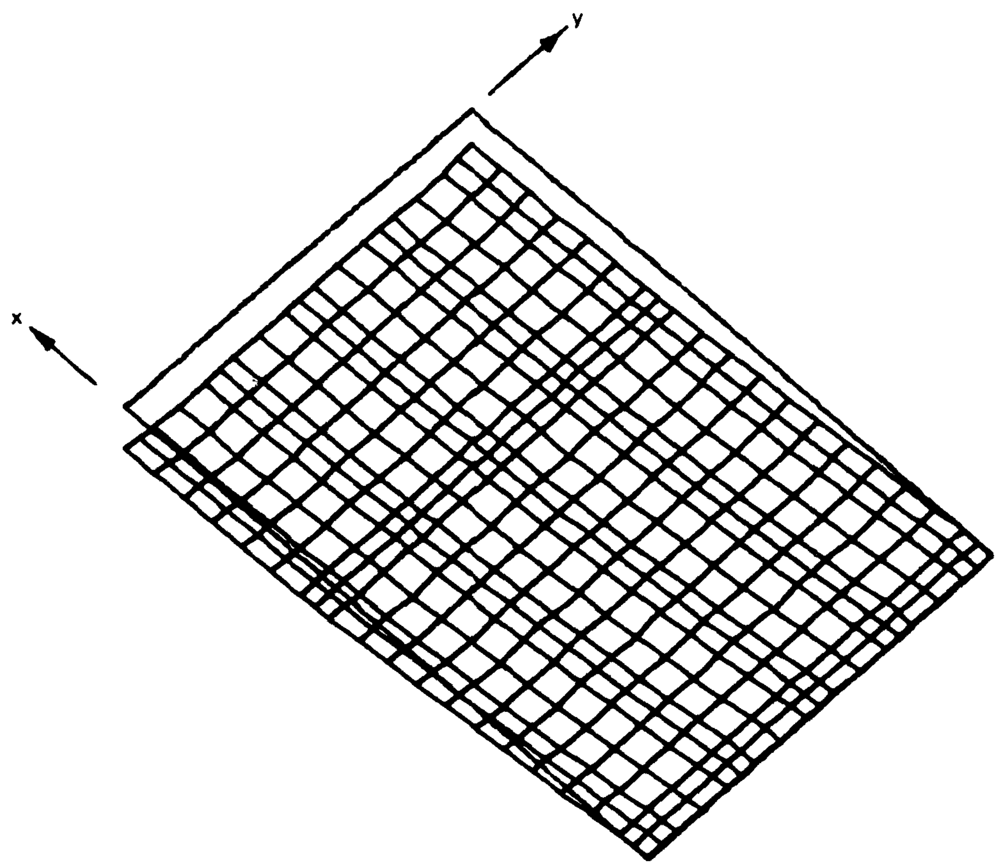

Figure 25. Displacement plot for bulkhead problem

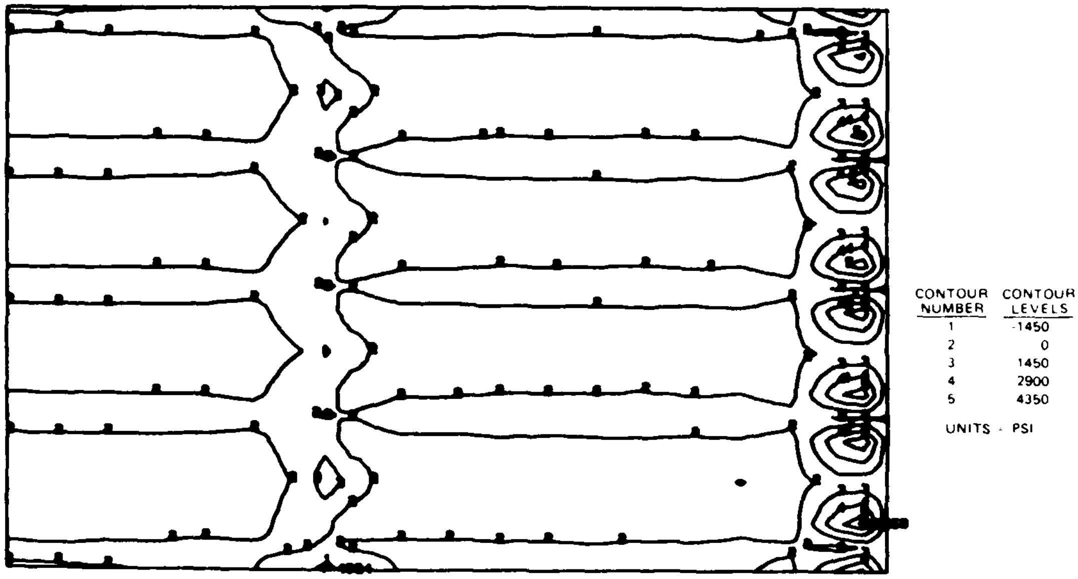

Figure 26. σ_x stress plot for bulkhead problem

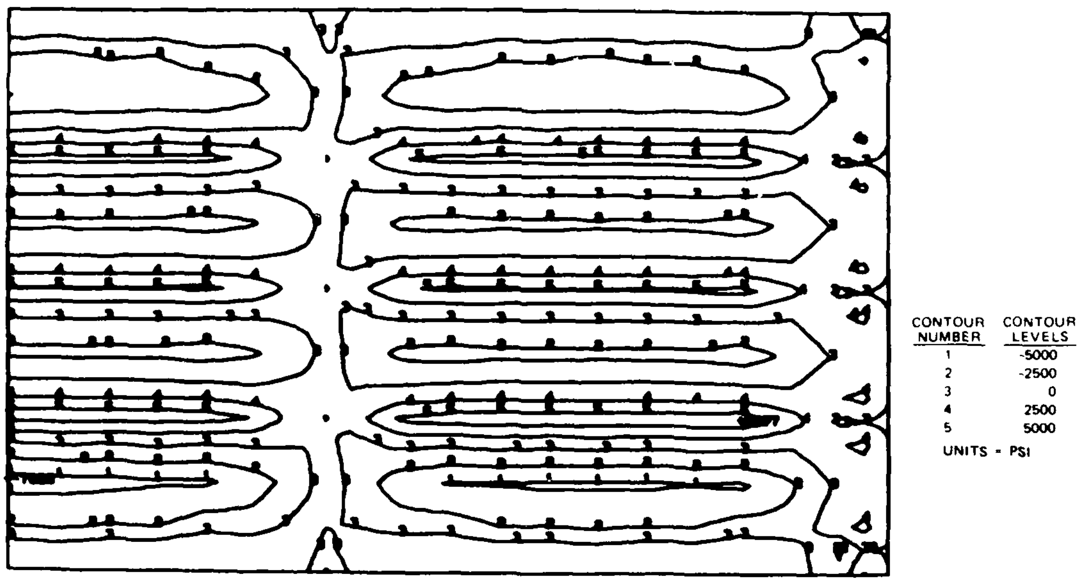

Figure 27. σ_y stress plot for bulkhead problem

Table 6

Costs of Analyses (Execution Costs Only)

	MCAUTO STRUDL	GTSTRUDL	E^3SAP	SAP	ANSYS	SUPERB
Bulkhead	\$185-\$294	(\$159-\$226) (3692 ccu)	(\$46-\$65) (1054 ccu)	(\$90-\$115) (4328 ccu)	(\$158-\$223) (3650 ccu)	\$86-\$278
Lock wall	\$62-\$97	(\$78-\$110) (1802 ccu)	(\$21-\$29) (475 ccu)	(\$26-\$43) (1221 ccu)	(\$25-\$35) (580 ccu)	\$42-\$139

Note: First figure is for delayed processing, second for 4-hr turnaround; ccu denotes Boeing Computer Services billing unit.

d. Which GPP is the easiest (for me) to use? (This consideration should include pre- and post-processing.)

e. Which GPP can handle this problem most realistically?

29. Caution should always be exercised in the selection of elements. Element behavior should be checked using problems with known answers. The suitability of the element for the type of problem being solved is very important. Documentation of the problem according to ETL 1110-2-254 can help the reviewers in their analysis and review of the results.

PART III: COMPARISON OF GENERAL-PURPOSE PRE- AND POST-PROCESSORS

Pre-Processors

General-purpose pre-processors

30. Many GPP's have node and element generation along with graphics capabilities which preempt the need for a pre-processor. However, many pre-processors have been developed to support one or more GPP's and/or to produce a universal data file. The universal data file can then be converted from its own format to the format of the GPP to be used. If the pre-processor generates a specific data file for the GPP, then no intermediate processing is required. Pre-processors that are specific to only one GPP were not included in this study. Instead, three general-purpose pre-processors that can be used with many GPP's were selected for comparison: SUPERTAB (Boeing), FASTDRAW (MCAUTO), and TRACY (WES).

31. Each pre-processor uses a somewhat different philosophy for generating grids. Some require more "homework" before beginning generation than others. Most pre-processors are interactively executed, which is more expensive than batch runs. Therefore, before beginning a computer session with a pre-processor, the user should have a complete outline of steps to be taken as well as a list of desired plots. Although interactive graphics sessions can be expensive, they can be great time savers and are a necessity in FE analysis.

Selection

32. The selection of a pre-processor should be based on which pre-processor can be used to generate the desired grid in the shortest period of time. Time should include both processing time and man-hours needed to prepare and run the problem. Capabilities for load generation, boundary conditions, and BW reduction should also be considered.

Results

33. Costs of using the three pre-processors for generating the geometry of the two problems are shown in Table 7. The pre-processors were used to generate the nodes, elements, boundary conditions, loads, and plots of the data for verification. Appendix F presents the responses of each task group member who used the assigned pre-processor. The WES pre-processor (TRACY) is not as

Table 7

Pre- and Post-Processor Cost Comparisons

	Problem	TRACY Macon	TRACY Boeing	SUPERTAB (Boeing)	FASTDRAW (MCAUTO)	IPVIEW (MCAUTO)
Pre-processing	Lock wall	$ 8	$15	$88	$87	N/A
	Bulkhead	$10	$18	$76	$71	N/A
Post-processing	Lock wall	$ 9	$17	N/A	$69*	$14*
	Bulkhead	$12	$21	N/A	$52*	$25*

Note: Figures which resulted from pre- and post-processing are listed in paragraph 35.
* Cost to display a previously created plot file.

sophisticated as the others. However, the results clearly indicate that it also is not as expensive as the others.

Post-Processors

Post-processors used

34. Use of post-processors becomes a necessity, especially when using computer-generated grids. A post-processor is designed to interactively display output data from a GPP. Three post-processors were used for comparison: SUPERTAB (Boeing), FASTDRAW (MCAUTO), and TRACY (Macon and Boeing). Currently (1982), FASTDRAW only supports the display of deflection and stress data from the GPP NASTRAN with interactive commands. This allows the NASTRAN user the ability to interactively plot different figures without reexecuting the program. Subsequently, FASTDRAW was used only to display plot files created by STRUDL. The same plots were viewed using the program IPFVIEW (MCAUTO) which is a cost-effective, special-purpose program for displaying plot files. Responses of the users of the post-processors are given in Appendix F.

Results

35. Each post-processor was used to produce the following (see Part II for all cited figures):

a. Lock wall problem:

Grid	Figure 18
Deformed shape	Figure 20
Contour plot of σ_x stresses	Figure 21
Window of contour plot of σ_x stresses	Figure 22
Contour plot of σ_y stresses	Figure 23
Window of contour plot of σ_y stresses	Figure 24

b. Bulkhead problem:

Grid	Figure 19
Deformed shape	Figure 25
Contour plot of σ_x stresses	Figure 26
Contour plot of σ_y stresses	Figure 27

36. In addition to contour plots, post-processors such as TRACY provide for vector plots of data.

Selection

37. The selection of a post-processor should be based on which

processor will yield the best plots for the least time and cost. Many of the GPP's generate output data files for either a specific post-processor or a file which can be reformatted for any post-processor. GPP's which do not provide for any post-processing should only be used for short, simple problems with well-ordered node and element numbering.

Costs

38. Costs of using the post-processors are shown in Table 7. Again, the WES post-processor (TRACY) is not as sophisticated as the others but is adequate for most two-dimensional FE analyses. It is also much less expensive than the other more sophisticated post-processors.

PART IV: SUMMARY AND REMARKS

Summary

39. The purpose of the study was to provide information to Corps structural engineers on several GPP's for FE analyses that would enable them to:

- a. Choose a GPP and general-purpose pre- and post-processor more intelligently.
- b. Estimate relative costs of using the GPP's.

Six GPP's were used to solve two sets of cantilever beam problems and two "real world" problems. Information on relative costs and on the efficiency of each was generated.

Remarks

40. At its inception, the study was though to be a rather simple task that could be achieved in a matter of days because most of the task group members were experienced FE program users and because no difficulty was anticipated in modeling or running of the problems. As the study progressed, however, it was found that the results generated for the problems using the different GPP's were not the same, and closer scrutiny indicated that there were some data errors. In addition, judgment was necessary in selecting element types for all problems. Comparison of the initial bulkhead results was particularly startling. Differences in results were found to be caused by various functions including:

- a. The use of different stretching and bending plate elements in the different GPP's.
- b. The manner in which shear areas (for computing shear effects) were handled in the beam members in the GPP's.

Further, all elements (or their equivalents) were not available on every GPP. Element behavior documentation was very poor on several of the GPP's, especially on SAP.

41. In general, there were a number of difficulties in running the problems on the various GPP's. If experienced users have difficulty, it can be assumed that inexperienced users will likely have even more difficulty.

42. Since different GPP's could use different formulations for their

elements, the user should carefully examine the relevance of the elements for modeling his particular problem. This caution is particularly necessary when plate or shell elements are being used. If the elements, boundary conditions, loads, and material properties are properly selected, there should be little difference in the results for a problem, irrespective of the GPP used.

43. To ensure consistent results, it is strongly recommended that all FE analyses used in Corps projects be documented according to ETL 1110-2-254. Without using this procedure, it is difficult in many instances to ascertain whether the results obtained are correct and reasonable.

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APPENDIX A: *COMPARISON OF FEATURES OF GENERAL-PURPOSE PROGRAMS*

(Initial version of this Appendix was prepared
by William Boyt, Structures Laboratory, WES)

Table A1

Comparison of Features of General-Purpose Programs

NOTE: These programs are periodically updated and improved; therefore, this comparison may not necessarily be up-to-date.

Comparison Categories	WES SAP	Boeing E^3SAP	MCAUTO STRUDL	GTSTRUDL	ANSYS	SUPERB
I. Input						
A. Free or fixed format	Fixed	Fixed	Free*	Free*	Free or fixed	Free or fixed
B. Node generation	X	X	X	X	X	X
C. Element generation (2D & 3D)	X	X	X	X	X	X
D. Bandwidth/wave front minimizer	X	X	X	X	X	X
E. Substructuring	X		X		X	
F. Pre-processor plotting						
1. Off-line, Tektronix, or both	Both	Both	Both	Both	Both	Both
2. Is any manipulation of data needed before plotting can take place?						
a. Off-line	No	No	No	No	Yes**	Yes**
b. Tektronix	Yes	No	No	No	No	No
3. Can input plotting be interactively changed w/o requiring job resubmission?	No	Yes	No	Yes	No	No
4. Printer plotting in batch w/o user manipulation?	No	No	Yes	Yes	No	No
II. Analytical Model						
A. Static						
1. Linear	X	X		X	X	X
2. Nonlinear			†		X	
B. Dynamic	X	X	X	X	X	X
C. Heat transfer					X	X
D. Analysis restart capability		X††	X‡	X‡	X	X
E. Analysis	X	X	X	X	X	X
F. Design						
1. Steel			X	X		
2. Concrete			X‡‡	X‡‡		

(Continued)

* Also, many commands are order-independent; i.e., problem-oriented language.
** Nashville District-developed software.
† Nonlinear capabilities support.
†† Dynamic analysis only.
‡ GTSTRUDL and MCAUTO STRUDL data base management offers SAVE, RESTORE, ADDITIONS, CHANGE, etc., commands.
‡‡ Per American Concrete Institute Standard 318-77.

Table A1 (Continued)

Comparison Categories	WES SAP	Boeing E^3SAP	MCAUTO STRUDL	GTSTRUDL	ANSYS	SUPERB
III. Element Library						
A. 1-Dimensional (truss, rod, bar)	X	X	X	X	X	X
B. 2-Dimensional						
1. Plane stress	X	X	X	X	X	X
2. Plane strain	X	X	X	X	X	X
3. Axisymmetric	X	X			X	X
4. Plate	X	X	X*	X**	X	X
5. Membrane	X	X	X	X	X	
6. Thin shell	X	X	X	X	X	X
7. User input (stiffness matrix)	X		X	X*	X	X
8. Beam	X	X	X	X	X	X
9. Truss	X	X	X	X	X	X
10. Pile	X	X	X	X		
C. 3-Dimensional						
1. Beam	X	X	X	X	X	X
2. Truss	X	X	X	X	X	X
3. Pile	X	X	X	X		
4. Boundary	X	X	X		X	X
5. Brick (8 nodes)	X	X	X	X	X	X
6. Brick (9 or more nodes)	X	X	X	X	X	X
7. User (stiffness matrix input)	X		X	X*	X	X
8. Pipe	X	X	X		X	
IV. Material Properties						
A. Linear	X	X	X	X	X	X
B. Nonlinear			†		X	
C. Anisotropic	X	X	X		X	X††
D. Temperature-dependent	X	X	X		X	
E. Reverse loading					X	

(Continued)

* Flexibility or stiffness matrix input for members; rigidity matrix input for finite elements.
** "Plate" elements are the superposition of plane stress and plate bending. Both STRUDL programs also have a "plate bending" element in which only bending deformations are considered.
† Trusses only.
†† Allows for orthotropic material properties.

(Sheet 2 of 4)

Table A1 (Continued)

Comparison Categories	WES SAP	Boeing E^3SAP	MCAUTO STRUDL	GTSTRUDL	ANSYS	SUPERB
V. Applied Loadings						
A. Point	X	X	X	X	X	X
B. Pressure*						
1. Uniform	X	X	X	X	X	X
2. Hydrostatic	X	X**	X**	X**	X	X
C. Prestress					X	
D. Specified displacements	X	X	X	X	X	X
E. Multiple load cases	X	X	X	X	X	
F. Combination of independent load cases	X	X	X	X	X	
VI. Analysis Capability						
A. Stress analysis						
1. Displacement						
a. Large†					X	
b. Small	X	X	X	X	X	X
2. Strain						
a. Large†					X	
b. Small	X	X	X	X	X	X
3. Thermal effects	X	X	X	X	X	X
B. Stability analysis						
C. Soil-structure interaction (slip or interface elements)			††		X	
VII. Output						
A. Printed						
1. Input echo	X	X	X	X	X	X
2. Error diagonistics	X	X	X	X	X	X
3. Global deflection	X	X	X	X	X	X
4. Global reactions	X	X	X	X	X	X
5. Member deflections	X	X	X	X	X	X
6. Member forces or stresses	X	X	X	X	X	X
7. Maximum stresses (element)	X		X	X	X	X
8. Selective output	X		X	X	X	X

(Continued)

* Variable (limited to specific elements).
** For some elements only.
† May or may not be linear.
†† Nonlinear support.

(Sheet 3 of 4)

Table A1 (Continued)

Comparison Categories	WES SAP	Boeing E^3SAP	MCAUTO STRUDL	GTSTRUDL	ANSYS	SUPERB
VII. Output (Continued)						
B. Graphic post-processor plotting						
1. Off-line, Tektronix, or Both	Both	Both	Both	Both	Both	Both
2. Is any manipulation of data needed before plotting can take place?						
a. Off-line	No	No	No	No	Yes*	Yes*
b. Tektronix	Yes	No	No	No	No	No
3. Printer plotting on batch w/o user manipulation?				Yes		
VIII. Graphic Plotting						
A. Pre-processing						
1. Interactive grid generation			X	X**	X	
2. Grid plots	X	X	X	X	X	X
3. Load plots					X	
4. Element shrink plots					X	
5. Batch grid generation				X		
B. Post-processing						
1. Deformed shape	X	X	X	X	X	X
2. Stress contours			X	X	X	X
3. Displacement vector plot						
4. Stress vector plot						
5. Strain contours			X		X	X
IX. Documentation						
A. Data preparation manual	X	X	X	X	X	X
B. Theoretical manual	X	X	X		X	X
C. Programmer's manual						
D. Validation problems and results	X	X	X	X	X	X
X. Support Available At	WES	Boeing	McAuto	Georgia Tech	Boeing, McAuto, Swanson	SDRC†
A. Currently being maintained	X	X	X	X	X	X
B. Currently being enhanced	X	X	X	X	X	X
XI. Computer Available on	WES Macon	Boeing	McAuto	Boeing	Boeing, McAuto	Boeing, Infonet

* Nashville District-developed software.
** Yes, but limited.
† SDRC - Structural Dynamics Research Corporation.

(Sheet 4 of 4)

APPENDIX B: DOCUMENTATION OF LOCK WALL PROBLEM ACCORDING TO ENGINEER TECHNICAL LETTER 1110-2-254

Introduction

1. General Description. The example problem documented here concerns a typical concrete gravity lock monolith. Dimensions were selected to provide an example problem that demonstrates use of a general-purpose program (GPP). The lock monolith is assumed to be located on a rock foundation consisting of a rather weak shale. (A sketch of the geometry of the structure is shown in Figure 16.) The monolith is 131 ft high with a base width of 110.25 ft. The wall culvert is 14 by 14 ft and is located 5 ft above the base.

2. Objective of Analysis. This analysis was performed to develop a benchmark finite element (FE) analysis of a concrete gravity lock monolith using the E^3SAP code. It will be used to develop data for comparison with data from other GPP's in the CASE report, "Case Study of Six Major General-Purpose Finite Element Programs."

3. Reference to Previous Work. Normally, a conventional stability analysis would be performed on the structure to determine its geometry; i.e., width of base, size of toe, etc. However, because of the purposes for which this analysis will be used, this step is not necessary. Other FE analyses of this problem have been performed using the GPP codes GTSTRUDL, MCAUTO STRUDL, ANSYS, SAP, and SUPERB. Results of these analyses will be compared with the E^3SAP results.

Description of Problem

4. Geometry and Materials.

   a. Lock wall. The concrete gravity lock wall is 131 ft high with a 110.25-ft base. A 14- by 14-ft culvert is located 5 ft above the base of the lock wall.

   b. Excavation. The structure is to be constructed in an open escavation. The excavation will remove overburden, sandstone, and shale.

   c. Foundation. The base of the structure is to be founded on shale. The properties of the foundation are:

Material	Modulus of Elasticity E , ksi	Unit Weight ksi	Poisson's Ratio v
Concrete	3000	0.15	0.25
Rock (shale)	27	0	0.41

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Rock (shale)	27	0	0.41

d. Backfill. Following construction, the landward side of the structure will be backfilled with a rock fill to el 379.0.*

5. Loads. For this example problem only loads due to the construction loading case will be considered. The excavation will be dewatered; thus, uplift and hydrostatic pressures will not be applied. Loads will be applied based on a rock fill with the following properties: unit weight = 125 pcf, ϕ = 35 deg, and ϕ = 22 deg. Lateral earth pressures are based on Coulomb's active earthfill coefficients.

6. Discussion of Why the Finite Element Method Was Used. The FE method was chosen for this problem in order to include it in the CASE task group's GPP report. However, conventional methods of analysis would not have been adequate for the type of problem selected for several reasons. The culvert opening creates areas of stress concentration within the structure which would have been difficult to calculate using conventional hand methods. A hand-computed stress analysis would have required simplifying assumptions as to distribution of shears and moments around the opening which might have led to less accurate or even erroneous results. In addition, use of the FE method allowed modeling of the structure-foundation interaction. Springs with varying stiffnesses were used based on the structural rigidity and the foundation modulus of subgrade reaction at each node along the rock-concrete interface. This type of interaction between the structure and foundation would not be considered in a hand-calculated analysis since the structure is usually assumed to be fixed to an infinitely rigid foundation.

7. Discussion of Finite Element Model.

a. This problem was idealized as a two-dimensional slice through the lock structure. A length of the lock was assumed to be sufficient such that the plane strain condition exists. A linear static analysis was performed with the foundation represented by linear springs.

b. For the FE analysis of the lock, Boeing Computer Services' E^3SAP program was used. E^3SAP was chosen because of its low cost and the user's familiarity with and confidence in the program.

c. The element used was the plane strain membrane element. This element is a general quadrilateral element with 2 degrees of freedom (DoF's) per node.

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* Elevations (el) are in feet referenced to mean sea level.

d. A verification study of this analysis was accomplished by comparison with an identical FE analysis performed using the other GPP's being evaluated.

e. The grid for the lock structure was developed to be refined in the area surrounding the culvert and coarse in the upper portions of the structure. All nodal points along the base of the structure were fixed in the horizontal direction and considered elastically supported by springs in the vertical direction. The dead load of the structure was included as a gravity load, while the backfill forces were applied as joint loads. The concrete was assumed to act linearly with a modulus of elasticity of 3000 ksi and Poisson's ratio of 0.20.

f. The grid chosen was considered fine enough for this problem since it was for comparison purposes only. The aspect ratios varied from 1 to 2 in the areas of interest surrounding the culvert and up to about 5.0 in the upper portions of the wall. No further grid refinement was necessary.

8. Finite Element Results. The results for the example loading case are shown in the form of deflected shape and stress contour plots (σ_x and σ_y) (Figures 20-24). Deformations for selected nodes are listed in Table 4. Since this was an example problem, only sufficient results for comparison to solutions from the other GPP's were obtained. Additional results would have been shown for a complete analysis.

9. Reduction of Results. Bending moments and thrusts can be obtained for selected sections using the shear, moment, and thrust calculation (CSMT) program (Figures B1 and B2). A summation of the reactions along the base in both the X and Y directions was made as an equilibrium check. Reactions were within 3 percent of the input loads.

10. Interpretation and Discussion of Results.

a. Examination of the base pressures indicates levels within the allowable maximum base pressures.

b. In the σ_x plots obtained using the TRACY post-processor, the bending in the wall culvert floor was anticipated and indicates behavior of the FE model consistent with the simplified approach of analyzing the floor slab as a beam. Moments, shears, and thrusts in this area would be obtained using program CSMT, and from these the reinforcing steel would be designed for this load case.

Summary of Analysis

11. The objective of this analysis, to provide a benchmark analysis for

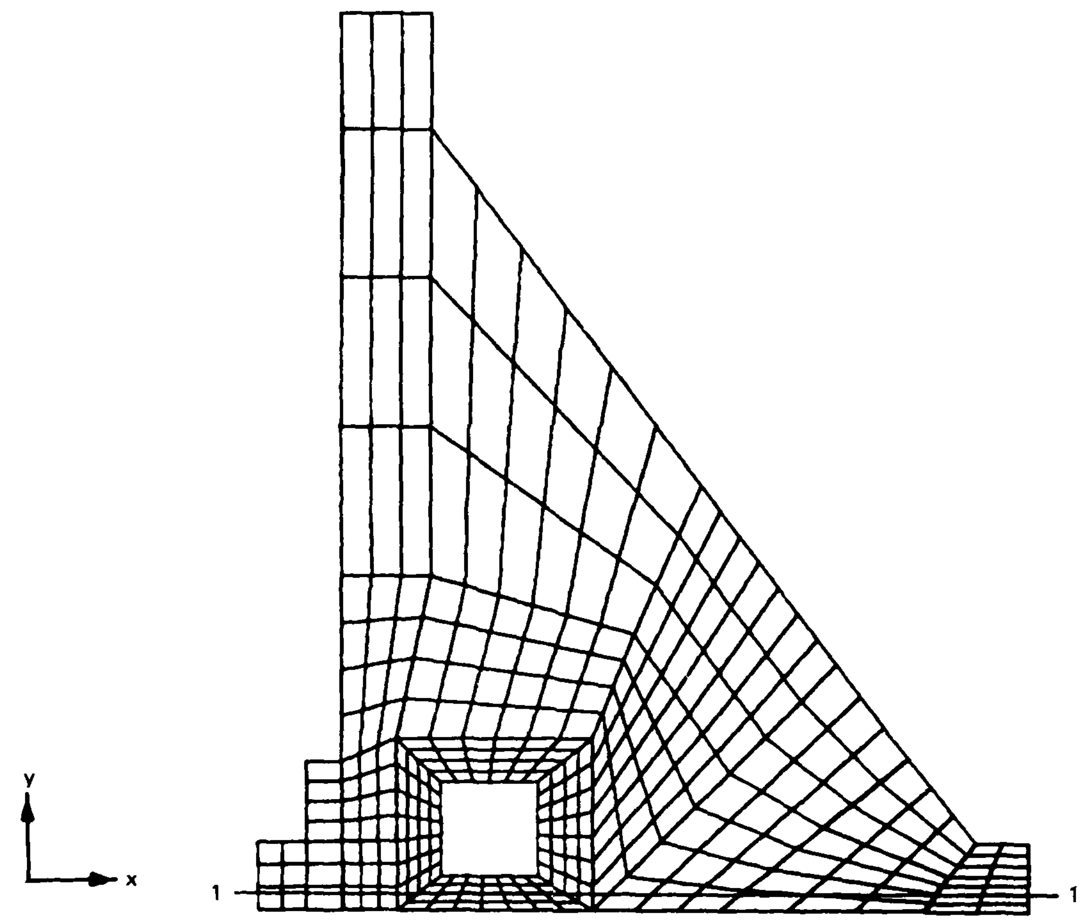


Figure B1. Plot of grid and section 1

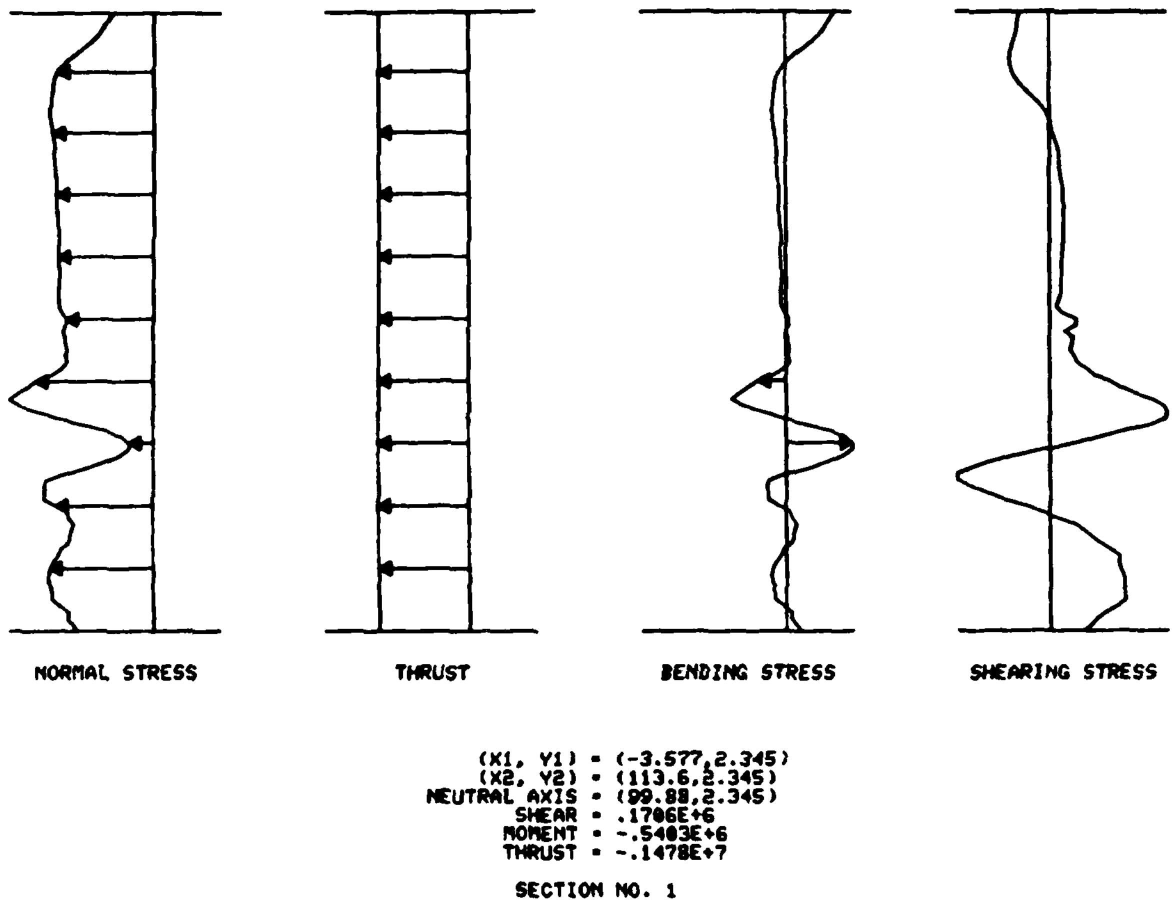


Figure B2. Output for section 1

comparison with analyses from other codes, was achieved. This analysis was able to show the capabilities of the code in analyzing this type of problem.

12. The deflections from this analysis will serve adequately in the benchmark comparison with other codes. However, it should be pointed out that an actual design problem might require a finer grid.

APPENDIX C: DOCUMENTATION OF BULKHEAD PROBLEM ACCORDING TO ENGINEER TECHNICAL LETTER 1110-2-254

Introduction

1. General Description. This finite element (FE) analysis models a steel bulkhead of the general type used in dams or other Civil Works structures. The dimensions were selected to provide an example problem that demonstrates use of a general-purpose program (GPP). The model used was not meant to be used for an exact analysis of a steel bulkhead since the program actually places the steel beams at the centroid of the skin plate. Section properties of the beams were adjusted to try to account for their eccentricity. A more "exact" analysis might be made by modeling the beams using stretching and bending plate elements rather than eccentric beam elements.

2. Objective of Analysis. This analysis was performed to develop a benchmark FE analysis of a steel bulkhead using the E^3SAP code. It will be used to develop data for comparison with data from other GPP's in the CASE report, "Case Study of Six Major General-Purpose Finite Element Programs."

3. Reference to Previous Work. A conventional analysis would be performed to verify the FE analysis. Other FE analyses of this problem have been performed using the GPP codes GTSTRUDL, MCAUTO STRUDL, ANSYS, SAP, and SUPERB. Results of these analyses will be compared with the E^3SAP results.

Description of Problem

4. Geometry and Materials. The bulkhead is a steel bulkhead constructed of horizontal and vertical beams with a watertight steel skin plate on one side. Its overall dimensions are 12 ft high by 36 ft wide. It has five horizontal beams spaced at 2 ft 9 in. and four vertical beams, two at the ends and two at 1/3 points. The skin plate is a continuous 1-in. steel plate that also forms one flange of the vertical and horizontal beams. End reactions from the horizontal beams are carried to the foundation by steel bearing shoes located on the skin plate under each horizontal beam.

5. Loads. The bulkhead was loaded using a horizontal water pressure load of 58 ft of head (3.62 ksf) at the top edge of the bulkhead varying uniformly to 70 ft of head (4.37 ksf) at the bottom edge. Structure self weight or any other loading was not considered. The bulkhead lies in the x-y plane, and loading is in the positive z direction.

6. Special Conditions. Because of the purpose for which this analysis

was developed, special conditions such as temperature gradients or structural defects are not considered.

7. Discussion of Why the Finite Element Method Was Used. The FE method was chosen for this problem in order to include it in the CASE task group's GPP report. However, the problem is of such a nature that conventional methods are not adequate. The behavior of a plate load in a normal direction as well as frames can be handled by conventional methods. However, the combination of a rigid frame with the action of the plate bending problem adds a complexity beyond a conventional analysis.

Discussion of the Finite Element Model

8. Problem Idealization. The stresses in the skin plate of the bulkhead are assumed to be caused by planar plate bending. The framing members are assumed to behave as members under pure bending. Beam-column action in the frame members is assumed to be small and will be neglected.

9. Program Selection. The program E^3SAP was selected from among the GPP's being studied. E^3SAP has the necessary element library and boundary condition capabilities to properly analyze this problem.

10. Element Selection. The SAP type 6 element was used for the skin plate. The type 6 element is a quadrilateral plate and shell element. This element is assumed to lie within the x-y plane having 4 nodes with 5 degrees of freedom (DoF's) per node:

a. x displacement.

b. y displacement.

c. z displacement.

d. σ_x rotation.

e. σ_y rotation.

The σ_z rotation is fixed since it is an unused degree of freedom.

11. The frame members are modeled with type 2 SAP elements. The type 2 element accounts for displacements from axial forces, shear forces, bending, and torsion.

12. These elements are not compatible since they have different DoF's and assumed displacement functions but provide an adequate model for this problem.

13. Verification Study. Verification of this analysis was accomplished

by comparison with identical FE analyses performed on the other GPP's.

14. Finite Element Modeling. The idealization of the bulkhead consisted of treating the skin plate as three-dimensional bending plate elements and the bulkhead stiffeners as line elements with beam properties. The model consisted of half of the subject bulkhead with a line of symmetry midway between the edge supports. The edge supports were treated as simple supports. Boundary conditions along the line of symmetry consisted of vertical restraint and rotational restraint about the global y axis. Loading consisted of linearly varying pressure with a maximum value at the bottom of the model (at $y = 0$) and a minimum value at the top. This load acts in the global z direction. Material properties of all elements are the same and are based on steel with a modulus of elasticity of 29×10^6 psi and Poisson's ratio of 0.3. Figure 19 shows the FE idealization of the structure.

15. Validity of Grid. In general, most plate element aspect ratios were approximately 1 and in no case exceeded 2. Horizontal and vertical grid lines were established initially along the bulkhead stiffeners. Additional horizontal and vertical grid lines were developed to retain the aspect ratios discussed above. Mesh size was not varied since the loading was uniform and the structure had no obvious stiffness discontinuities of concern for this analysis.

16. Additional Items to Discuss for Dynamic Analysis. No dynamic analysis was required for this study.

Finite Element Analysis Results

17. For this analysis, only one loading case was run: a horizontal water pressure load as discussed in paragraph 5 of this appendix.

18. High stress zones in this structure are to be found at the center line of the bulkhead. For this analysis, the stresses in the skin plate and beam flanges for the five horizontal beams are reported. In an actual analysis, other areas, such as local bending stresses in the skin plate, shear stresses at the beam supports, and bending stresses in vertical beams, should be considered. The following is a tabulation showing element numbers and stresses at each beam center line:

Element No.	Bending Moment kip-in.	Skin Plate Stress, ksi	Flange Stress, ksi
1	18,348	19.11	18.86
20	18,810	13.14	17.01
39	18,133	12.67	16.40
58	17,444	12.19	15.78
77	15,830	16.48	16.27

19. The maximum values of displacements for this structure are to be found at the center line. Table C1 lists displacements of the skin plate nodes at the center line. Figure 25 is a deflected shape plot of the skin plate and the beams showing overall bending shapes.

Table C1

Center-Line Displacements for Bulkhead Computed by E^3SAP

Node No.	Displacement, in.
1	-0.3355
2	-0.3647
3	-0.3990
4	-0.4286
5	-0.3980
6	-0.3795
7	-0.3853
8	-0.4011
9	-0.3808
10	-0.3683
11	-0.3750
12	-0.3863
13	-0.3630
14	-0.3517
15	-0.3623
16	-0.3808
17	-0.3480
18	-0.3143
19	-0.2850

Reduction of Results

20. Program Output. Program output for this program consists of node displacements and rotations; plate stresses at the center of each element; and axial forces, shear forces, twisting, and bending moments for beam elements.

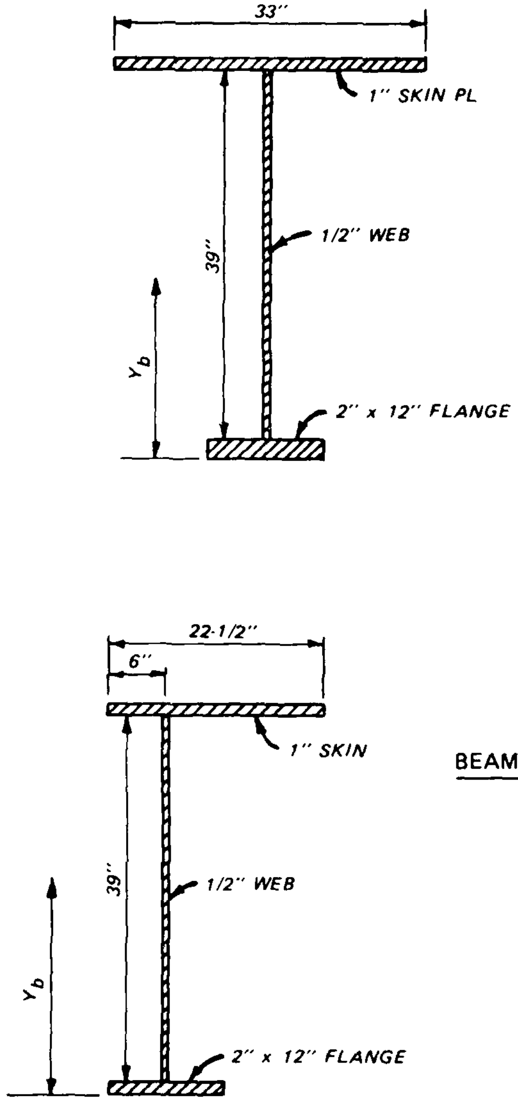
These can be used in standard fashion to find beam stresses. In this run, the final stresses in the skin plate must be obtained by algebraically adding local stresses in the skin plate caused by bending moments M_{xx} and M_{yy} to the stresses caused by beam bending moments M_2 and M_3. Bending moments M_{xx} and M_{yy} are reported in the output of the program under "PLATE/SHELL ELEMENT STRESSES AND MOMENTS"; M_2 and M_3 are reported under the heading "BENDING ELEMENT FORCES AND MOMENTS." Plate element stresses are computed by dividing the moments M_{xx} and M_{yy} by the section modulus for the skin plate. Similarily, beam bending moments M_2 and M_3 are computed by dividing by the appropriate beam section modulus. The following computation table gives an example of this procedure:

Element No.	Moments, kip-in. M_{xx}	M_{yy}	M_2	M_3	Stresses, ksi: Skin Plate Stress S_{xx}	Skin Plate Stress S_{yy}	Total Skin Plate Stress S_{yy}	Beam Flange Stress
Plate El 1	-0.0064	-0.289	--	--	-0.04	-1.73		
Beam El 1	--	--	0	18,348	0	-19.11	-20.84	+18.86

The skin plate section modulus equals 0.167 in.^{3}; the beam skin plate section modulus equals 960.28 in.^{3}; and the beam flange section modulus equals 972.84 in.^{3}. See Figure C1 for geometry properties.

21. Interpretation and Discussion of Results. A conventional analysis based on simple beam theory was performed for the horizontal beams with tributary areas of skin plate. Results of the simple beam theory analysis and the FE analysis are shown below:

Element No.	FE Moment, kip-in.	Simple Beam Moment, kip-in.	FE Skin Stress, ksi	Simple Beam Skin Stress, ksi
1	18,348	15,807	19.11	16.25
20	18,810	22,267	13.14	20.14
39	18,133	21,350	12.67	19.31
58	17,444	20,132	12.17	18.48
77	15,830	13,305	16.48	13.68



BEAM ELEMENTS 21 THRU 80

AREA = 76.5 IN.^{2}
Y_b = 23.696"
I = 26200.2 IN.^{4}
S_{FLANGE} = 1105.68 IN.^{3}
S_{SKIN} = 1431.40 IN.^{3}

BEAM ELEMENTS 1 THRU 20, 81 THRU 100

AREA = 66.0 IN.^{2}
Y_b = 20.864 IN.
I = 20296.9 IN.^{4}
S_{FLANGE} = 972.84 IN.^{3}
S_{SKIN} = 960.28 IN.^{3}

Figure C1. Section properties for bulkhead

These results compare reasonably well. The FE model appears to distribute the overall load more uniformly to the edge beams than the simple beam assumption of tributary area.

22. Table 5 shows the comparison of typical deflections along the line of symmetry for the GPP's evaluated.

23. Since the purpose of this analysis was to provide a baseline for

comparisons with several other GPP's, a number of modeling simplications were made which influenced the behavior. Among these are:

a. Artificially inducing the eccentricity of the beam centroid from the skin.

b. Not considering the deadweight of the structure.

These assumptions have a major influence on the results and essentially preclude use of this arbitrary model for accurate determination of element loads and displacements.

24. Equilibrium Check. The total load applied to the model was equal to 852.92 kips, and the summed reaction was equal to 851.36 kips. Boundary constraints acted as expected and are explained in paragraph 14 of this appendix.

Summary of Analysis

25. The objective of this study, to provide a benchmark analysis for comparison with analyses from other GPP's, was achieved. This analysis was able to show the capabilities of E^3SAP in analyzing this type of problem. The differences in element types between this GPP and the others also became apparent.

26. It became apparent early in the modeling of this problem that an eccentric beam element would be needed to model the structure accurately. Another more expensive solution would have been to model the beam elements using an FE mesh and membrane elements. The second approach would give more "exact" answers, but the cost would normally be prohibitive for an engineering problem.

27. The stresses and deflections in this analysis will serve adequately in the benchmark comparison with other codes. However, it should be pointed out that an actual design problem might require a finer skin plate mesh and account for modeling the eccentricity of beam elements.

APPENDIX D: LISTING OF COSTS FOR VERIFICATION OF GPP RUNS/DATA

MCAUTO STRUDL

Lock wall pre-processing:	\$ 87.00
a. FASTDRAW model creation	
Lock wall post-processing:	\$172.00
a. Geometry	
b. Deflected shape	
c. Normal stress X contour	
d. Normal stress Y contour	
Bulkhead pre-processing:	\$ 71.00
a. FASTDRAW model creation	
Bulkhead post-processing:	\$ 52.00
a. Geometry	
b. Deflected shape	
c. Normal stress X contour	
d. Normal stress Y contour	

E^3SAP (Boeing)

Lock wall pre-processing:	\$120.00
a. Grid plot (unnumbered)	
b. Numbered grid plot	
c. Window of numbered grid plot	
d. Geometry	
Lock wall post-processing:	\$400.00
a. Deformed shape	
b. Deformed grid with numbers	
c. Window of deformed grid with numbers	
d. Deformed shape plot over geometry	
e. Window of shape plot over geometry	
Bulkhead pre-processing:	\$140.00
a. Frame grid plot with nodes numbers	
b. Frame grid with element numbers	
c. Total grid plot without numbers	
d. Total grid plot with node numbers	
e. Total grid plot with element numbers	

E^3SAP (Boeing) (Continued)

Bulkhead post-processing:	$170.00
a. Deformed shape	
b. Rotated deformed shape	
c. Window of deformed shape with element numbers	
d. Window of deformed shape without numbers	
e. Window of deformed shape with node numbers	
f. Total deformed shape with node numbers	

GTSTRUDL (Boeing)

Bulkhead pre-processing:	$ 49.00
a. Geometry plot (BATCH)	($ .10)
b. Consistency check and reduce bandwidth (BATCH)	($ 48.00)
Bulkhead post-processing:	$310.00
a. Deflected shape plot (interactive)	
Lock wall pre-processing:	$ 35.00
a. Consistency check and reduce bandwidth (BATCH)	
Lock wall post-processing:	$160.00
a. BATCH - Geometry/deflected shape plot	$ 7.00
b. BATCH - Contour plots of σ_x and σ_y	$153.00

APPENDIX E: ELEMENTS USED

GTSTRUDL Elements

Lock wall: IPLQ

Bulkhead:

Skinplate--SBCRCSH

Beam--Beam element

For details of elements, see the GTSTRUDL User's Manual which can be purchased from Boeing Computer Services.

SAP Elements

Lock wall: Type 4

Bulkhead:

Skinplate--Type 6

Beam--Type 2

For details of elements, see the SAP User's Guide which can be obtained from the Engineering Computation Program Library (ECPL) at the U. S. Army Engineer Waterways Experiment Station.

E^3SAP Elements

Lock wall: Type 4

Bulkhead:

Skinplate--Type 6

Beam--Type 2

For details of elements, see the E^3SAP User's Manual which can be purchased from Boeing Computer Services.

MCAUTO STRUDL Elements

Lock wall: IPLQ

Bulkhead:

Skinplate--PBSQ2

Beam--Beam element

For details of elements, see MCAUTO's STRUDL User's Manual which can be purchased from McDonnell-Douglas Automation Company.

ANSYS Elements

Lock wall: 2-D isoparametric solid

Bulkhead:

Skinplate--Rectangular shell

Beam--Beam element

For details of elements, see the ANSYS User's Manual which can be purchased from Boeing Computer Services or Swanson Analysis Systems, Inc., Houston, Pa.

SUPERB Elements

Lock wall: Plane strain quadrilateral

Bulkhead:

Skinplate--Thin shell

Beam--Beam element

For details of element, see the SUPERB User's Manual which can be purchased from Structural Dynamics Research Corporation, Milford, Ohio.

APPENDIX F: COMMENTS ON PRE- AND POST-PROCESSORS

MCAUTO FASTDRAW (Richard Flauaus, St. Louis District)

1. Ease of initial use - Fairly difficult. This is due to its vast capabilities. I feel that a simple problem should be run to gain an understanding of the procedures prior to running a difficult problem. There is no step-by-step procedure to follow.

2. Comments on capabilities (Did it do what you wanted?) - Yes! The capabilities of FASTDRAW are excellent but expensive. FASTDRAW can mesh a specified region by merely specifying only the points on the outer boundaries of the region.

3. Support available - MCAUTO STRUDL, NASTRAN, ANSYS, SAPV, EASE.

4. General comments - The use of FASTDRAW was beneficial for the lock wall problem due to the complicated geometry. However, I feel that, if I were assigned a problem similar to the one on the bulkhead, I would have used just the internal mesh generating capabilities of STRUDL to create the model. It should be noted that, by using FASTDRAW, I was able to create all elements, members, and support conditions.

TRACY Pre-Processor (Tom McGee, Nashville District)

1. Ease of initial use - Very easy initial use. Easy to follow user's manual, good graphics.

2. Comment on capabilities (Did it do what you wanted?) - Fairly flexible for 2-D grids if boundary zones are chosen carefully. Would like to see mid-side node capability added.

3. Support available - Yes.

4. Response of computer system - Reasonable on Macon. Not as good at WES. This program and the TRACY post-processor should run very well on the Corps' new Harris minicomputers.

5. Cost of engineer time on examples - Lock wall problem - 4 hr.
- Bulkhead problem - 8 hr.

6. General Comments - This program was run at Macon for both examples. "Engineer time" includes the time to prepare working material (rough sketch, boundary coordinates, etc.) necessary to run the program, and the time it took to reformat the data to be compatible to run a GPP on another system.

TRACY Post-Processor (Tom McGee, Nashville District)

1. Ease of initial use - Once the data from a FE run have been manipulated to the proper format, use of the program is quite easy. Manual is complete and easily followed. Graphics are good.

2. Comments on capabilities (Did it do what you wanted?) - Very flexible graphics since it is up to the user to decide what items are plotted and nature of plot. One improvement to the program might be to internally calculate the centroid of each element rather than having it be an input item. Some codes do not print this information.

3. Support available - Yes.

4. Response of computer system - I ran the program at Boeing and would say the response was reasonable to good. I would expect the response at Macon to be a little slower. Again, this would be an excellent program to be converted to run on the Corps' new Harris minicomputers.

5. Engineer time on example - Lock wall problem - 8 hr.

6. Cost of computer time - 252.435 ccu's on Boeing.

7. Total time and cost to complete an example - 2 hr, 45 min.

8. General comments - "Engineer time" includes all time spent to retrieve and reformat FE data to the proper form and get familiar with the user's manual, and the time spent at the terminal running the program.

- Calcomp plotting not currently available on Boeing system. This should be added with an option of retrieving the plot file at the District for plotting on in-house plotter.

SUPERTAB Pre-Processor (Robert Hall, WES)

1. Ease of initial use - Very much like other general-purpose preprocessors. The initial use serves more as a learning session rather than an actual producing session.

2. Comment on capabilities (Did it do what you wanted?) - Program was very flexible and could be used to generate any grid needed for the Corps' structural work.

3. Support available - Supported with capable staff and documentation.

4. Response of computer system - Response time at Boeing was acceptable.

5. Cost of engineer time on examples - Lock wall, 3 hr; bulkhead,

2 hr (hours are not those of an initial user).

6. Cost of computer time on examples - Lock wall, $115; bulkhead, $95.

7. General comments - This program generates grids for GTSTRUDL, ANSYS, SUPERB, NASTRAN, and a universal file which can be reformatted for other GPP's. The program is very versatile and complete. Support provides for generation of nodes, elements, and boundary conditions as well as loads.

APPENDIX G: GLOSSARY

Bandwidth - A stiffness matrix is sparse, and all nonzero terms are clustered in a band along the diagonal. This band includes, in any row, terms on both sides of the diagonal. The number of terms in this band is the bandwidth of the matrix (Cook 1974).

Wave front (frontal solution) - The frontal solution works element by element using only the part of the stiffness matrix belonging to the front. The solution efficiency is a function of element order (not node order) (Zienkiewicz 1977).

Benchmarking - A cost comparison study of computers or computer applications for solving a representative set of problems.

Fixed format - Type of input for computer applications which is based on fixed fields.

Free format - Type of input for computer applications which is not dependent on fixed field.

Substructuring - Separating a part of the grid from its surroundings and determining its solution separately for any prescribed displacements at the interconnecting boundaries (Zienkiewicz 1977).

Off-line plotting - Plotting of data on a device separated from the computer.

On-line plotting (Tektronix plotting) - Plotting of data on a time-sharing graphics device.

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